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Institutionalizing the Electric Warship

Abstract:

The Navy has invested a considerable amount of resources in developing Electric Warship technology in the past twenty years. We have witnessed a number of early technology demonstrations as well as incorporation of IPS technology into ship programs such as LHD 8, T-AKE, DD(X), and CVN 21. While these early adopters have paved the way for establishing the practice of electric warship design, we are now at a critical point in time for institutionalizing the electric warship. A technology is institutionalized when the following activities have occurred:

- Establish a common architecture and interfaces
- Establish a common design processes
- Incorporate the architecture and design processes into design tools
- Codify the practice in Government or Industry specifications, standards and guides.
- Teach the architecture and design process as part of a typical Engineering School Curriculum.

This paper reviews the progress in electric warship technology, describes progress (including ongoing efforts) in institutionalization, highlights critical near term shortcomings. Some of the shortcomings in design processes and tools include:

- Undefined (in authoritative documentation) concepts such as Zonal Survivability and Quality of Service.
- Obsolete requirement terms such as “sustained speed” and “Endurance speed / range”
- Conflicting design practices for propulsion and ship service prime mover sizing.
- Customized system protection strategies for different classes of ships.
- Ambiguous methodologies for the sizing of zonal distribution system components.
- Lack of integration of IPS design algorithms into ship concept tools such as ASSET.
- Lack of knowledge as to how to effectively use modeling and simulation to make electric plant design decisions for each stage of ship design.

Additionally, the paper details progress in updating standards and specifications such as the Naval Vessel Rules and DOD-STD-1399. Finally, efforts to incorporate Electric Warship design into the curriculum at traditional Naval Architecture are described.

INTRODUCTION

In the early stages of the deployment of a new technology, engineers and customers spend considerable effort understanding the capabilities of the new technology, as well as the best ways to exploit the technology. Often, the technology is not well matched with pre-existing design methodologies, standards, design tools, and production processes. Often a new “requirements language” must be developed to enable the customer to efficiently communicate the desired capabilities that the new technology offers. If these issues are not addressed in a coherent manner, each application of the new technology would require reinvention of the methods, tools, and processes to incorporate the technology in each product. Each reinvention offers the opportunity for error, rework, and a considerable investment of resources, enough so that the product designer may not consider the technology worth the bother. For lack of a better word, the author will use the term “institutionalization” to refer to the activities needed to facilitate incorporation of a technology into product design from the earliest stages of product design to product deployment.

The desired outcomes of institutionalization of a technology are:

- An engineer has sufficient knowledge of the technology to predict its performance and impact on the product design at all stages of design.
- An engineer has sufficient knowledge of the technology to predict the engineering effort required to integrate the technology into the product design in all stages of design
- An engineer has sufficient knowledge of the technology to predict the cost impact of the technology on the production cost of the end product.
- An engineer is able to adequately specify the technology in a product specification to enable the producer to adequately bid a price and produce an acceptable product.
- A customer is satisfied with the performance of the end product, having only characterized the performance requirements with relatively few parameters. In other words, customer expectations are met for product performance in areas that have not been explicitly specified.

In the end, institutionalizing a technology reduces the cost, schedule, and performance risk associated with incorporating a technology into a product. A low risk technology that will meet product requirements is more likely to be chosen by the designer than a higher risk technology.

The Navy has invested a considerable amount of resources in developing Electric Warship technology in the past twenty years. ONR, NAVSEA, and the acquisition program offices have funded a number of technology demonstrations and component developments. These have culminated in the incorporation of Integrated Power System (IPS) technology into ship programs such as LHD 8, T-AKE 1, DD(X), and CVN 21. While these early adopters have paved the way for establishing the practice of electric warship design, we are now at a critical point in time for institutionalizing the electric warship to ensure the successful incorporation of IPS into future ship classes.

INSTITUTIONALIZING TECHNOLOGY

To achieve the desired outcome described in the Introduction, the following steps are proposed:

- Demonstrate the Technology Early
- Incorporate the basic technology into Production Units
- Establish a common architecture and interfaces
- Establish a common design process
- Incorporate the architecture and design process in design tools
- Codify the practice in Government or Industry specifications, standards, and guides
- Teach the architecture and design process as a standard part of a typical Engineering School Curriculum

In general, while these steps are listed somewhat in order that they are typically completed, accomplishment of the work often overlaps. (Figure 1)

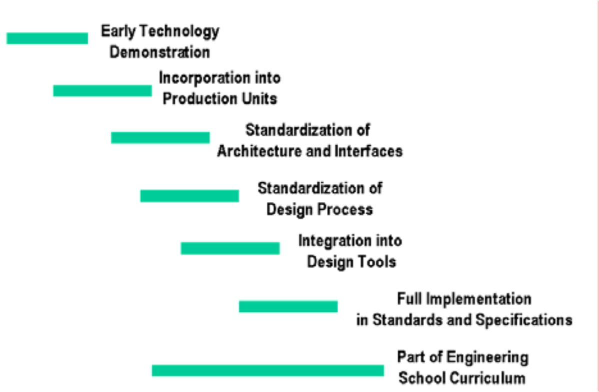

Figure 1: Institutionalizing Technology Steps

Demonstrate the Technology Early

Much is learned by the actual design, construction, and use of a product employing a new technology. Many times, the problems and successes of a technology demonstration will greatly impact the manner in which future systems are designed and used. Customers can use knowledge gained from the demonstration to develop new Concepts of Operation (CONOPS) and provide achievable requirements to the acquisition community for new programs. Technology Demonstrations also help identify and quantify previously unknown or underappreciated technical risks while at the same time retiring previously identified risks.

Incorporate the basic technology into Production Units

Although much is learned in early technology demonstrations, even more is learned when the technology is applied to production units intended for use by the end customer. Strengths and weaknesses in architecture, design processes, design tools, and standards are all revealed when designing a system "for real." In technology demonstrators, the R&D community performs the design, integration, fabrication, and testing. In a production environment, entirely different organizations with their entrenched tools, processes, and facilities are involved. Often, previously unknown or underappreciated technical risks are identified and must be mitigated for the product to be a success. For those producing the technology, it is vital to capture the lessons learned from these "early adopters" and incorporate them into the other steps for institutionalizing the technology.

Establish a common architecture and interfaces

Tom DeMarco (1995) provides the following definition of "architecture:"

"An architecture is a framework for the disciplined introduction of change. This is also a pretty good definition of design. The difference between the two is that design, as we commonly use the word, applies to a single product, while architecture applies to a family of products."

As a framework, an architecture defines the boundaries of a system to include functional interfaces with external systems, partitions the system into functional elements, describes the behavior of the functional elements, and describes the allowed interaction between functional elements.

The architecture of a system forms the basis for partitioning the required work into tasks, establishing organizational boundaries for accomplishing the tasks, determining the schedule and deliverables for each task, and the methods for integrating the products of multiple teams into a single system that is testable. Often, a systems architecture is more important to managing the risks of the design and production process than it is to the operation of the end product. Through sheer will of effort, one can usually make a single complex system work without an established architecture, but likely to a cost and schedule that was not previously predicted.

As indicated by DeMarco, a good architecture is one that can accommodate change in a disciplined manner. The source of the change can be evolving requirements of a specific product, or different sets of requirements for different products. In the end, a good architecture reduces the risk of incorporating the technology in new products.

Establish a common design processes

During the initial applications of a technology, a variety of design processes and techniques are typically explored. Some will work, others will not. Some design processes will prove themselves overly cumbersome; others will not be robust enough to ensure a satisfactory product is manufactured. Some design methods will only work for a narrow range of applications. For other methods the required resources and schedule required will be unpredictable. While this early experimentation is very valuable in developing a good workable design process, eventual convergence on a common design process is extremely valuable for the following reasons:

- The design process can be measured and improved through continuous process improvement methodologies
- The design process can provide repeatable results with known quality and risks.

- The design process can provide the basis for estimating required engineering and production effort, thereby improving cost estimation
- The design process forms the basis for the development of design tools and educating the workforce to improve the quality of the product with less engineering effort.

Incorporate the architecture and design processes into design tools

Good design tools are essential to well engineered systems. Engineering decisions are based on predicted performance; the success of a design depends on how robust the design is to deviations from the predicted performance as well as the accuracy of the prediction. A good architecture with its associated interface standards should provide the necessary design robustness. Design tools are needed to provide the prediction accuracy.

Design tools also facilitate a consistent implementation of a design process so that it is repeatable and produces results of a consistent quality. If design tool development reflects the evolution of the architecture and design processes, then design tools can become a mechanism for capturing all of the lessons learned during the early application of the technology. In fact, data derived from analyzing the first applications of the technology is critical to the verification and validation of the design tool.

Codify the practice in Government or Industry specifications, standards and guides

Codifying the technology interface specifications and design practices in Government and/or Industry specifications, standards, and guides enables industry to develop products designed to fit within the overall architecture. These products can be designed and qualified independent of a hard application requirement; the producer can be confident that as part of the larger architecture, that a customer for the product can be found.

For the system designer, good standards and specifications enable efficient communication between the designer and the component producers, helping to ensure that the products delivered will meet their intended purposes. In this way, specifications and standards reduce technical, schedule and cost risk.

Teach the architecture and design process as part of a typical Engineering School Curriculum.

An educated workforce is always critical to the sustained success of a new technology. In the initial applications of a technology, the education is largely "On-The-Job-Training." Textbooks and courses covering the technology and its associated design processes do not exist at the undergraduate level, and may not be comprehensive at the graduate level. Knowledge is generally shared through personal contact, professional journals, symposiums, and short courses. Eventually however, new engineers are expected to know how to apply the technology and follow the appropriate design processes. At this stage, developing the appropriate curriculum at engineering schools is important in professionally developing the workforce.

STATUS OF INSTITUTIONALIZING THE ELECTRIC WARSHIP

Technology Demonstrations

IPS Technology demonstration is well documented from the early days of Reduced Scale Advanced Development and Full Scale Advanced Development (Doerry and Davis 1994) (Doerry et. al. 1996), through the Integrated Fight Through Power (IFTP) demonstrations (Zgliczynski et. al. 2004), and culminating in the DD(X) Engineering Development Models (EDMs). Technology demonstrations continue for future improvements in such areas as fuel cells, permanent magnet motor technology, silicon carbide power electronics, superconducting motors and generators, energy storage, directed energy weapons, and advanced inverter designs.

Production

While DD(X), currently completing Contract Design, will be the first U.S. Navy warship to fully implement IPS with the DC Zonal Electrical Distribution System, electric warship technology is also being introduced in other classes of ships. *Lewis and Clark* (T-AKE 1) is the lead ship of a new class of replenishment ships that has a commercially derived integrated power system. (Sauer and Thompson 2004) *Lewis and Clark* will be delivered to the U.S. Navy in 2006. *Makin Island* (LHD 8) is the first gas turbine amphibious warfare ship with all electric auxiliaries in the U.S. Navy. (Dalton et. al. 2002) In addition to her mechanical drive gas turbines, she also has two 5000 hp auxiliary propulsion motors powered from diesel generator sets. *Makin Island* is expected to deliver to the U.S. Navy in early 2008. Dusang (2005) provides a good description of the "Early Adopter" system and ship integration issues faced by the designers of *Makin Island*. The Navy's newest aircraft carrier design, CVN-21, will also incorporate a zonal electrical distribution system and all electric auxiliaries. (Antonio 2005) CVN-21 is currently scheduled to deliver to the U.S. Navy in 2014.

Common Architecture and Interfaces

The basic IPS architecture described by Doerry and Davis (1994) is generally common among all recent electric warship designs. The actual interface standards however, continue to evolve. In general, the prime movers generate medium voltage ac power between 4.16kV and 13.8kV (figure 2). Propulsion motor modules are directly connected to the medium voltage distribution system. Ship Service loads are provided power via either a zonal ac or zonal dc distribution system. Auxiliary and Amphibious ships tend to use zonal ac distribution systems (Figure 3) where in-zone load centers are powered via medium voltage to 450 VAC transformers. Combatants, such as DDX use zonal dc systems (figure 4) in the form of Integrated Fight Through Power (IFTP) to provide better power quality and quality of service.

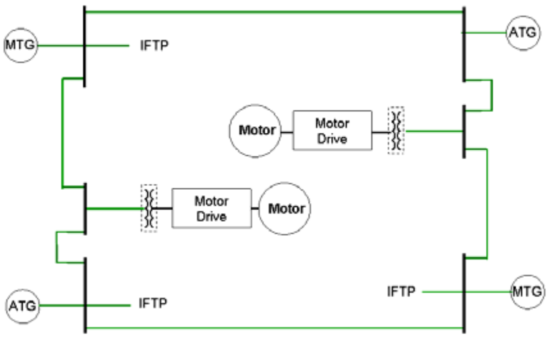

Figure 2: Notional Medium Voltage AC Distribution System

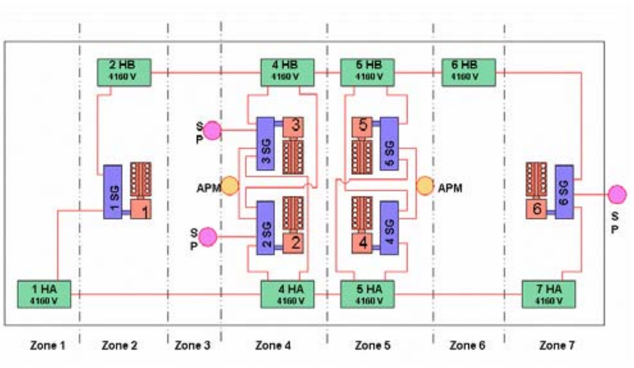

Figure 3: Notional AC-Zonal Distribution System

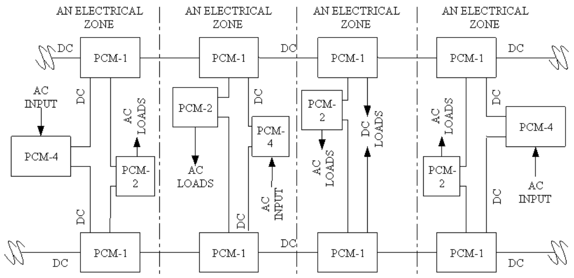

Figure 4: Notional DC-Zonal Distribution System

Common Design Processes

Design processes for Electric Warships are still evolving. Many early stage ship concept designers are still unfamiliar with how to best employ IPS technology to maximize capability while minimizing cost. Unfortunately, many designers restrict themselves to general arrangements and machinery arrangements that differ minimally from a traditional mechanical drive plant and do not take advantage of the architectural flexibilities offered by an Integrated Power System. Additionally, lack of understanding of power system design constraints imposed by fault current interrupting capability of breakers, reliability considerations, power quality, and quality of service often lead to infeasible power system designs in early concept studies.

In power system design, a number of key design processes still require refinement and consensus. These include refinements in the load analysis process to account for zonal loads, power quality, and quality of service; refinement in "requirements" terms such as sustained speed and endurance speed to provide guidance in power generation sizing; development of methods for power distribution equipment sizing for zonal distribution systems; allocation of system protection functions among power conversion equipment, circuit breakers, electric plant controls etc.; establishment of design criteria for the incorporation of energy storage modules; and the establishment of a consistent margin policy for each element of the power distribution system.

Currently, no single document exists that describes a process for the successful design of an electric warship. While a proposed IPS Design Data Sheet was created as part of the IPS Full Scale Advanced Development (Martin Marietta Corporation CDRL B005), this document has not been kept up to date to reflect advancements in IPS technology and design methodology over the past ten years. Other papers describe general issues associated with zonal design (Doerry 2005) and designing power systems to account for Quality of Service (Doerry and Clayton 2005).

Design Tools

Design Tools, especially early stage tools such as the Advanced Surface Ship an Submarine Evaluation Tool (ASSET) are not yet capable of developing optimized electric warship designs. These tools are in general based on design methodologies for mechanical drive ships. Where electric drive is supported, it is usually done within the paradigm of mechanical drive ship design. The synthesis models are often not sensitive to the potential benefits of electric drive.

To date, the work-around has been to design an IPS configuration external to the ship synthesis tool, then use payload adjustments and other techniques to enable the ship synthesis tool to properly represent the IPS configuration. Unfortunately, this process is labor intensive and very error-prone.

One barrier to successfully modeling IPS in ship synthesis tools is the awkwardness of fitting IPS systems within the Ship Work Breakdown System (SWBS). IPS modules currently span multiple SWBS groups. Furthermore, because SWBS elements no longer have a configuration managed data dictionary, it is often unclear which SWBS groups an IPS component should fit in. In a number of cases, detailed review of ship concepts has revealed "double counting" and omission of elements within the SWBS structure. This issue if further compounded when cost estimators apply inappropriate cost estimating relationships to the ambiguous SWBS elements.

Tools to support Preliminary and Contract design are also lacking. The Electric Plant Load Analysis (EPLA) for example, does not currently account for quality of service. Similarly, the proper use of simulation tools to ensure proper transient operation and system stability is not well understood. Tools to help determine and design the grounding systems also do not currently exist.

Specifications, Standards and Guides

IPS and the electric warship are based on a number of concepts that are not explicitly defined, or are not adequately detailed in "official" government and industry documents. These concepts include:

- Zonal Survivability
- Quality of Service

- DC Power Interfaces
- Medium Voltage AC Power Interfaces
- Machinery Control System Standards
- System Stability design methods
- System Grounding practices

Efforts are currently underway to update the applicable sections of the Naval Vessel Rules (NVR) and MIL-STD-1399 to reflect evolving IPS design practice. Under consideration for inclusion in NVR based on IPS testing is more rigorous qualification of propulsion motor insulation systems. Multi-megawatt pulse width modulated converters driving propulsion motors with high current density stators present stresses to insulation systems which are not well characterized by traditional insulation accelerated life testing methods. New methods to better assess insulation degradation factors are under consideration by international standards setting bodies and being incorporated into Navy development programs. With respect to evolving power interface standards, IFTP provides the opportunity to "customize" the power interface to better support ship mission systems. Currently an Electric Power Interface Working Group (EPIWG) is chartered with establishing new interfaces for DD(X) mission power systems. Both ac and dc interface standards are being refined to better support COTS power supplies and reduce mission system conversion steps in addition to meeting the requirements of legacy loads designed to DOD-STD-1399. The requirements are being captured in the DD(X) design specification working from the format used in DOD-STD-1399 such that they can be easily incorporated when finalized. The EPIWG has industry representation from shipbuilding, mission system design, and power system design as well as Navy stakeholders from ship design and warfare systems.

Engineering School Curriculum

While the design of Electric Warships is part of the concept level design of several Post Graduate naval engineering programs, these programs typically treat IPS components at the module level and do not address all aspects of IPS integration. The development of IPS component technology is also an integral part of a number of University research programs. In general however, the design of IPS systems is not addressed in depth. This situation largely reflects the lack of maturity of IPS design processes and the emphasis of university curriculum on teaching Systems Engineering at a higher conceptual level.

In the past year, some progress has been made in educating the ship design community on the issues of electric warship design through the development of a Summer Naval Surface Ship Design Program that was first taught in 2005 at the University of Michigan. Designed for the professional development of engineers both in Government service and in industry, this summer program consisted of five 1 week courses followed by a 2 week capstone course. Two days of this program were dedicated to electric warship design. While the format of future offerings of this program will likely evolve, electric warship design will continue to be taught.

CONCLUSION

The first steps of institutionalizing the electric warship are nearing completion. Technology demonstrations are either already complete or underway. "Early Adopter" ships such as the *Lewis and Clark* (T-AKE 1), *Makin Island* (LHD 8), and CVN 21 are in detail design and construction while DDX is in the final stages of Contract Design.

While a lot of progress has been made, much work remains. Many technical issues such as zonal survivability, quality of service, DC Power Interfaces, Medium Voltage AC Power Interfaces, Machinery Control System Standards, System Stability design methods, and System Grounding practices require greater formalization and incorporation into design processes, tools and standards. Ship synthesis tools in particular need improvement to ensure electric warship capabilities are properly employed in ship concept designs as well as ensuring assumed electric power system designs are indeed feasible.

Investment is also needed in educating the ship design and HM&E systems designers to properly design future electric warships. Eventually, the naval architecture and naval engineering curriculums at our leading universities must reflect the electric warship design processes.

Once these steps are complete, we will have finally institutionalized electric warship technology.

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