1989-2014

The Evolution of the Electric Warship

by Dr. Norbert Doerry

The end of the Cold War marked the beginning of a multi-decade evolution of the surface combatant into the Electric Warship. At ASNE Day 1989, Dr. Cy Krolick and CAPT Clark (Corky) Graham presented the concept of Technology Clusters to advocate the synergistic research and development of surface combatant technology. Technology Clusters promised to enable concurrent systems engineering and component R&D, provide programmatic stability, and decrease fleet introduction time. The first cluster, Cluster A, consisted of integrated electric drive, advanced propulsor system, ICR gas turbine, integrated electrical distribution system with pulse power, machinery monitoring and control, advanced auxiliary system, and low observability/loiter power system. The foundational Cluster A would be an enabler for the introduction other clusters, most notably, Cluster E, Electromagnetic Pulse Power. Over the next several decades, these technologies would mature, be incrementally introduced into ship designs, and culminate in the delivery of the first modern electric warship to the U.S. Navy that featured an Integrated Power System (IPS), *USS Zumwalt* (DDG 1000). Modern electric power technology has also been introduced into auxiliary ships (T-AKE 1 class and MLP 1 class), amphibious warship ships (LPD 17, LHD 8 and LHA 5 class), aircraft carriers, submarines, and into DDG 51 flight upgrades. Furthermore, directed energy weapons such as the Laser Weapon System (LaWS) are beginning to be fielded, and the Electromagnetic Railgun (EMRG) is currently transitioning from an Innovative Naval Prototype (INP) into a weapon system technology development program. High power radar, such as the Air and Missile Defense Radar (AMDR), have also been enabled by increased electric power availability from electric warship technology.

Integrated Power System

While a number of studies and projects in electrical propulsion and electrical power system technology were conducted in the 1960s and 1970s, the efforts leading to the incorporation of IPS on DDG 1000 probably began in November 1979, with a series of studies under the Advanced Integrated Electric Propulsion Plant Conceptual Design (AIEPP) project managed by NAVSEA (Joliff and Greene 1982). During the early 1980s, the Navy began the design of DDGX (future DDG 51 class). Heavily influenced by AIEPP, electric drive was chosen as the baseline propulsion system during the DDGX preliminary design. This decision, however, was reversed in the contract design phase due to concerns over cost and schedule risk, as well as a perceived lack of expertise within the Navy and industry design and engineering workforce. As a result, the traditional mechanical drive plant used in the DD 963 and CG 47 classes was employed in the DDG 51 class.

In September 1988, Chief of Naval Operations Admiral Carlisle A.H. Trost stated in a speech to the Navy League:

> Integrated electric drive, with its associated cluster of technologies, will be the method of propulsion for the next class of surface battleforce combatants, and I am directing all the major Navy organizations involved in these efforts to concentrate their energies toward that objective.

Aligned with this declaration, the Integrated Electric Drive (IED) program emerged to develop a very quiet and power dense electric propulsion system for a future surface combatant. General Electric was awarded a contract to develop prototype hardware in November 1988. This hardware included a 120 Hz., 6 phase, 4160 vac, 25 khp, 3600 rpm very quiet rotating machine that could serve as either a generator or as a geared propulsion motor.

In 1991, the Soviet Union collapsed, ending the Cold War. With the end of the Cold War and the Nation's desire for a "Peace Dividend," the Navy could no longer afford to develop a future surface combatant (The DDG 51 class having just been introduced). The IED program was developing an expensive technology that did not have a transition path to a ship design. In 1991, the IED program came under the Advanced Surface Machinery Programs (ASMP) under the direction of Captain Corky Graham and Dr. Cy Krolick.

In the fall of 1991 and spring of 1992, ASMP engineers expended considerable effort to reduce the cost of the IED system and to take advantage of commercial technology. Reflecting the new austere fiscal reality, Captain Graham redefined program objectives from increasing military effectiveness at greater cost to making systems more affordable without degrading performance. Since the more ambitious acoustic performance of the IED system would likely not be needed in the coming decades, these studies found that other emerging technologies could produce more affordable power systems than what was achievable with the IED system. Consequently, ASMP focus shifted away from completing the IED program. Some IED hardware was delivered to the Navy, but was never tested.

In 1992, the basic architecture of IPS and the different module types was established. Doerry and Davis (2004) described the IPS architecture:

> The Integrated Power Architecture (IPA) provides the framework for partitioning the equipment and software of IPS into modules. IPA defines six functional elements and the power, control, and information relationships between them. Every IPS module corresponds to one of the IPA functional elements. A power relationship is one involving the transfer of electrical power between two functional elements. A control relationship refers to the transmission of commands from one functional element to another while an information relationship refers to the transmission of data from one functional element to another. The six functional elements are Power Generation, Power Distribution, Power Conversion, Power Load, Energy Storage, and System Control.

The IPS concept in 1992 also included a Product Line approach. Generalized modules would be engineered ahead of their application for a specific ship following an open architecture defined by evolving baselines. These modules would be described by Module Characterization Sheets, which provided the necessary information to integrate them into a system as well as the necessary specifications and standards to procure the modules. An IPS Design Data Sheet would provide the process for developing an IPS configuration by tailoring the individual modules to meet the ship requirements.

The electric power system baselines were intended to ensure that technologically current and viable IPS solutions would always exist for new naval ship designs. If the Navy needed a power dense, quiet electric drive system in the near term, then ASMP would propose a system based on the IED program. This set of technology was called Baseline 1, and reflected the then-current program of record. Since an affordable system for an amphibious warfare ship or auxiliary ship could not be based on Baseline 1, a power system based on militarizing commercial technology would be proposed. This was called Baseline 2. Both baselines would be supported by specifications, standards, handbooks, design data sheets, and design tools. Ongoing S&T and R&D efforts would eventually result in Baseline 3 replacing Baseline 1, with a more affordable power system architecture for combatants, and a future Baseline 4 would similarly replace Baseline 2 for amphibious warfare and auxiliary ships. These baselines anticipated the Product Line approach to technology development.

IPS also incorporated provisions for an AC zonal distribution system and a DC zonal distribution for ship service loads. A modified version of the AC zonal distribution system was later incorporated in the Flight IIa of DDG 51 (see Petry and Rumburg 1993), LPD 17, and LHD 8. The DC zonal distribution system became the Integrated Fight Through Power (IFTP) system that transitioned to DDG 1000 as part of IPS. IPS was viewed as an enabler for the electric warship, and offered the following opportunities for ship design (Doerry and Fireman 2006):

Support High Power Mission Systems

An electric warship enables all power generated to be available for ship service needs. As envisioned by Krolick and Graham's Technology Clusters, the large amount of available power enables many new technology weapon system elements, such as high power radar, electromagnetic guns, electromagnetic launchers, and laser weapons. Not only will the weapons themselves change, but also the manner in which they integrate into the ship. For example, as electric weapons replace conventional guns and missiles, ship systems such as magazines, weapons handling gear, ship safety, and protection systems will also radically change.

Reduce Number of Prime Movers

Electric Warships enable fewer prime movers to service higher power loads. For example, a conventionally designed LPD 17 has 9 rotating machines with the equivalent of 43 mw of total ship power: four medium-speed, diesel prime movers along with five diesel generators. An IPS-based new design, LPD could be configured using only four prime movers. Fewer prime movers can result in better fuel efficiency, reduced acquisition cost, reduced maintenance, and reduced manpower requirements.

Improve Efficiency of Prime Movers

Overall system efficiency of an IPS configuration can be higher than for an equivalent mechanical drive design. The overall efficiency of a mechanical drive ship can suffer because the propulsion prime movers are inefficient at low ship speed and generator sets are often lightly loaded. With IPS, ship service and propulsion loads are managed off the same distributed system-enabling efficient loading of prime movers.

Improve Efficiency of Propulsors

With an IPS, the propulsion shaft line can be simplified with the removal of the traditional controllable pitch propeller (CPP) system. Alternate technologies, such as contra-rotating propellers or POD Propulsion are enabled. The improved performance of POD propulsion has been recognized by the builders and operators of merchant ships, and is featured in many ferries, cruise ships, and other commercial ships. Contra-rotating propellers can also improve efficiency. Since many propulsion motors feature two independent motors on the same shaft, dedicating each motor to its own propeller does not add significant complexity. Designing long-life bearings to support the inner shaft is an engineering challenge, but achievable. Alternately, a hull mounted shaft and propeller can be paired with a POD to provide contra-rotation.

Provide General Arrangements Flexibility

The electric warship enables challenging conventional ship design rules. Traditional ship designs locate prime movers low in the ship to align with the shafts. An IPS provides the designer the flexibility to put generator sets in almost any location (subject to stability considerations). The shaft line can be simplified with direct drive motors. Future ship designers could also challenge conventional designs associated with the longitudinal separation of propulsors, improve survivability, and improve ship maintainability. IPS enables new approaches to combustion air and exhaust design.

Improve Ship Producibility

The elimination of long shaft-lines enables shipbuilders to simplify the erection schedule, and thereby reduce the ship construction schedule. By locating generator sets higher in the ship, the in-yard need date for these items can be delayed, reducing the likelihood that the equipment will be damaged during the ship's construction. Furthermore, each module can be tested before integration into the ship, reducing the risk that equipment will fail during the ship acceptance process. Zonal distribution systems shorten cable lengths and minimize the number of spaces a cable has to penetrate.

Facilitate Fuel Cell Integration

Fuel cells promise to improve the fuel efficiency of future naval power systems. Since fuel cells directly produce electrical power, their integration into an electrical power system is natural; Fuel cells are just another type of generator set. While the technical challenges of integrating fuel cells has limited their applications, these challenges are being addressed by the Navy and industry. At some time in the future, fuel cells will likely become viable; the electric warship will facilitate their introduction into the fleet.

In 1992, ASMP also began discussions with Newport News Shipbuilding and Kamen Electromagnetics to develop a Baseline 3 power system based on Permanent Magnet Motor technology. This technology promised to provide combatants high power density at a lower cost than Baseline 1. Baseline 3 was also intended to be capable of supporting future pulse power weapons, such as lasers and railguns. To demonstrate the Permanent Magnet Motor technology, ASMP established a Reduced Scale Advanced Development (RSAD) project that in 1994 resulted in the testing of a 3,000-hp, permanent magnet motor scaled as a prototype of a 25,000-hp motor.

In the fall of 1992, CAPT Graham focused IPS entirely on Baseline 3 since Baseline 1 was not affordable, and Baseline 2 didn't need any further development. Hence, IPS became the program for developing an integrated power system for the next combatant. Auxiliary ships, such as the T-AKE 1 class (and later the MLP 1 class), would use commercial marine IPS solutions, fulfilling the Baseline 2 concept.

In February 1995, NAVSEA awarded an IPS Full Scale Advanced Development (FSAD) contract to Lockheed Martin's Ocean, Radar, and Sensor Systems. The FSAD system was intended to serve as a test bed for technologies that could be incorporated in a future shipboard IPS architecture. As the systems integrator, Lockheed Martin was responsible for developing the standards, specifications, design data sheets, and handbooks for designing and integrating an IPS system. Unfortunately, while Lockheed Martin was an outstanding systems engineering organization to develop specific products, it was not a company accustomed to developing a product line. Much effort was expended to transition the knowledge gained in the systems architecting process conducted by the ASMP government team to help the contractor fulfill the envisioned role of IPS systems integrator. The mismatch between the need for a product line developer, and the capability of a product developer, was not resolved. Following the IPS FSAD contract, Lockheed Martin exited the IPS market.

In June 1996, an SC-21 (predecessor to the DDX program) IPS Ship Impact study compared IPS and mechanical transmissions. This study, conducted by the SC-21 Cost and Operational Effectiveness Analysis (COEA) team, found that the IPS ship cost $10 million less in acquisition, was 400 LT smaller, and consumed 17% less fuel. In March 1998, the SC-21 COEA report by CNA concluded IPS resulted in "significant reductions in ship design, construction, and life cycle costs"

The integration of IPS into the DD 21 program was described by Walsh (1999):

> In early 1999, senior Navy officials -including Adm. Frank L. Bowman, Director of the Navy's nuclear propulsion program, supported by Vice Chief of Naval Operations Admiral Donald L. Pilling; Vice Admiral George P. Nanos Jr., NAVSEA commander; Rear Admiral George R. Yount, deputy for engineering in NAVSEA; and Rear Admiral Joseph A. Carnevale Jr., program executive officer for the DD 21-initiated an effort to accelerate Navy electric drive work. In 1998, the IPS program was transferred from NAVSEA's Engineering Directorate to the PEO DD 21 (PMS 500). The fiscal year (FY) 1999 Navy budget provided $33.9 million for IPS, $4 million of which was targeted for the DD 21 Blue and Gold team concept studies. No funding was provided in the FY 2000 budget, however. Navy leaders are considering options for reprogramming funds from other programs for IED work during the year ahead.

As announced by the Secretary of the Navy, IPS became part of the DD 21 baseline in January 2000 (Bowman 2000). One consequence of moving IPS into a ship acquisition program was that the effort became focused solely on this one transition. The product line approach was largely abandoned as focus was placed on producing a product for the DD 21/DDX/DDG 1000. The module boundaries defined in 1992 were redefined into a ship-specific, Low Voltage Power System (LVPS) developed by DRS Technologies, and a High Voltage Power System (HVPS) developed by Converteam. While a test facility and a working Integrated Power System were developed, the vision for an IPS product line was not realized.

Initially, the IPS system for DDG 1000 was based on a Permanent Magnet Motor (PMM). In February 2005, however, delays in testing resulted in the design shifting to the fallback Advanced Induction Motor (AIM) and a 4160-volt distribution system to eliminate the need for a propulsion transformer. Subsequent testing, although too late for integration into DDG 1000, would prove the PMM ready for shipboard service. Likewise, an alternate technology, full-scale, superconducting, synchronous motor subsequently would also be successfully tested.

Advanced power system technologies were introduced into amphibious warfare and auxiliary ships as well. LPD 17, for example, incorporated a zonal ac distribution system. T-AKE 1 introduced a modern, commercially-based, integrated power system. LHD 8 introduced hybrid electric drive to the U.S. Navy (see sidebar)

The *Gerald R. Ford*-class (CVN 78) of aircraft carriers is also taking a step towards the electric warship. The electrical capacity for CVN 78 will be 2.5 to 3.0 times as much as that of the previous *Nimitz* class. Two significant electrical loads re the Dual Band Radar and the Electromagnetic Aircraft Launch System (EMALS). (PEO Aircraft Carriers 2013) EMALS will replace the steam catapults of previous carriers. The EMALS system is a multi-megawatt system that incorporates advanced power conversion, energy storage, and linear motors. (General Atomics 2013) The U.S. Navy is learning much from its integration into the carrier's electric power system.

Electric Ships Office

The Electric Ships Office (ESO or PMS 320) continues to mature naval power systems The ESO has its origins in the transfer of the IPS program from NAVSEA's Engineering Directorate to PEO DD-21 (PMS-500) in 1998. NAVSEA leadership was concerned that without a corporate approach to IPS development, the ability to use common elements across ship types would be severely limited. Following a study of the different alternatives, the Commander, Naval Sea Systems Command, signed out a report on 21 January 1999 recommending a Corporate Development Program for IPS. This Corporate Development Program, concurred to by SEA 03 (Now SEA 05), SEA 08, PEO DD21, PEO SUBS, and PEO CV, would develop a product line approach to benefit multiple platforms. This report also observed that the Radial-gap Permanent Magnet Motor was the most viable motor common to the broadest range of ships.

On February 18, 1999 the Integrated Power System Corporate Investment Board (CIB), composed of the NAVSEA and PEO organizational stakeholders, met to discuss the recent report and the strategy for funding the Corporate Development Program. A $503 million program schedule and budget was proposed. This proposal to stand up a new program with such a large cost was not well received by OPNAV, and was subsequently shelved.

FIGURE 1. An F/A-18E Super Hornet prepares to launch during a test of the Electromagnetic Aircraft Launch System (EMALS) at Naval Air Systems Command, Lakehurst, N.J. EMALS is a complete carrier-based launch system designed for *Gerald R. Ford* (CVN 78) and future *Ford*-class carriers. (U.S. Navy photo/Released).

USS Makin Island

By Dr. Norbert Doerry

One of the U.S. Navy's first application of modern electric warship technology is the hybrid electric drive (HED) on *USS Makin Island* (LHD 8). In *Makin Island's* HED system, a relatively small propulsion motor powered from diesel generators augments a gas turbine mechanical drive shaft. When operating at low speeds, the diesel electric drive motor is much more fuel efficient than the gas turbine operating at a small fraction of its rated load. This same system has been incorporated into the LHAs of the *America* class. For more specific technical details of the *Makin Island* HED and electric plant design, see (Dalton et al. 2002) and (Dusang et al. 2006)

Makin Island, commissioned in 2009, was not the first HED ship. The U.K. Type 23 frigates, first commissioned in 1990, employed a COmbined Diesel-eLectric And Gas turbine (CODLAG) propulsion system. These ships employ diesel electric propulsion for low speed quiet anti-submarine warfare (ASW) operations and gas turbine boost engines for high speed. Lessons learned from the Type 23 frigates were considered in the design of *Makin Island*.

A series of feasibility studies conducted over a number of years predated the decision to employ HED on *Makin Island*. (Hatcher et al. 2002) These studies evaluated the work and cost necessary to convert the steam propulsion to gas turbine propulsion on an LHD. The first study (Ingalls 1997) established feasibility for converting LHD 7 to gas turbine propulsion using an LM2500+ gas turbine to power each shaft. This study incorporated 800-hp loitering motors attached to the reduction gears to improve fuel efficiency and enable propulsion up to about 5 knots. The 450-volt electric plant was minimally modified, requiring auxiliary boilers to supply the over 7 MW of ventilation heating loads on cold days. For later LHDs, such as LHD 8, the study recommended eliminating the auxiliary boilers by installing a 4160-volt electrical distribution with six 4MW generators to supply the ventilation heater loads.

In response to this study, Commander, Naval Surface Force Pacific Fleet would only support a gas turbine LHD if all steam systems were removed. Due to circuit breaker limitations, extremely restrictive plant configurations, and the excessive weight of distribution cabling needed to supply the ventilation heating loads, a 450-volt electrical distribution system was dropped from further consideration.

The second study (Ingalls 1998) examined a 4160-volt electric plant with six 3.75-mw generators and two 1,000-hp loiter motors integrated with each reduction gear. A 4160-volt electric plant reduced risk of qualifying components by preserving commonality with aircraft carrier equipment. The larger, 1,000-hp loitering motors enabled 10 knots for loitering. Even with one generator out of service, enough electrical capacity remained on all but the coldest days to power the four, 1,000-hp motors. By using these motors, over $22 million in fuel savings were estimated for the 40 year service life of the ship.

The third study (CSC 2000) integrated a single 5,000-hp induction motor with each reduction gear. The 1800 rpm single speed induction motors did not use adjustable speed drives because of the risk of causing problems in electric plant operation due to increased harmonic currents and voltages. The 5,000-hp motors enabled 13 knots and matched the 4 MW rating for a single diesel generator set. This increased speed enabled the motors to be used during LCAC operations. The combined power demand of the two motors was less than the excess electrical generation capacity on all but the coldest of days.

The fourth study (Converteam 2001) evolved the electric plant design by replacing the 3.75 mw diesel generators with 4.0 MW diesel generators. The evolved design also implemented a shaft break-away torque requirement. Previous studies assumed the gas turbine would start shaft rotation before propulsion power shifted to the motors. Fleet operators found this concept of operation unsatisfactory; they were concerned that with only one gas turbine per shaft, should that one gas turbine become inoperative during restricted maneuverability or alongside a pier, the ship would be unable to break the shaft free and use the motor. The need to provide shaft break-away torque, and a more detailed analysis of the electrical system led to incorporating a commercially derived 24 pulse variable speed drive (VSD) with an 1800 rpm induction motor. Without a VSD, three paralleled generators would be needed to provide inrush current. The VSD enabled either a single dedicated generator to power the motor, or for two paralleled generators to simultaneously power the motor and serve ship service loads while meeting power quality requirements. (Dalton et al., 2002)

The ship specifications for the detail design and construction contract for LHD 8 incorporated this final configuration. No prototypes were produced because the HED only used non-developmental components. Because the integration risk was judged low enough, no land based testing of the integrated propulsion system and no integrated testing of the Machinery Control System were conducted prior to commissioning of the Auxiliary Propulsion System onboard the ship.

The design, production, integration, and testing of the HED on *Makin Island* was challenging. The Navy finally accepted delivery of LHD 8 on April 16, 2009 after months of frequent interaction among the Navy engineers, shipyard engineers, and the OEM engineers, many hours of testing and system grooming, and two sets of builders trials followed by acceptance trials. Additional grooming of the HED on her voyage from the shipyard to her homeport in San Diego, California optimized performance. *USS Makin Island* was commissioned on October 24, 2009. During his speech at the commissioning ceremony the Honorable Ray Mabus, Secretary of the Navy, remarked ...

> Just two months ago, *Makin Island*, our hybrid of the seas that uses an electric motor to power the ship at low speeds, went from where it was built in Pascagoula around to its homeport in San Diego. During that initial voyage alone, she saved close to $2 million in fuel costs. NAVSEA estimates at today's fuel prices *Makin Island* will save $250 million over the lifetime of that ship, and it doesn't include reduced maintenance costs....

The amphibious assault ship *USS Makin Island* (LHD 8) transits San Diego Harbor. (U.S. Navy photo by Mass Communication Specialist 3rd Class Timothy Schumaker/Released)

Converteam, "LHD-8 Loiter Motor Study II," NAVSEA Technical Instruction 006, July 13, 2001.

CSC, "LHD 8 Loiter Motor Trade-Off Study," for NAVSEA 05D, October 2000.

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Dusang, Louis V. Jr., David E. Whitehead, and John Fisher, "Commercial Protection Practices Applied to Naval Power Systems: A Case Study," Schweitzer Engineering Laboratories, Inc., TP6258-01, 26 October 2006.

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Ingalls Shipbuilding, "Alternate Propulsion Study LHD 7 WTA 2204.017 Phase 1 Technical Report - Feasibility Study," CDRL A258 Issue 013, Contract No. N00024-92-C-2204, 19 May 1997.

Ingalls Shipbuilding, "Gas Turbine LHD," WTA-2204-024, Contract No. N00024-92-C-2204, 4 Sept 1998.

In 2002, the Naval Research Advisory Committee (NRAC) bolstered the case for centralized management of electric warship technology in their *Roadmap to an Electric Naval Force* report:

> Electric weapons and advance, high-power, sensors offer the superior warfighting capabilities such as deeper magazines, longer range, higher rates of fire, precision strike, quicker time to target, and longer-range, higher-resolution sensors necessary for the 21st century environment. However, the large amount of electric power these systems will require makes current shipboard electric systems impractical. Making all shipboard power available electrically enables the integration of such advanced weapons and sensors to create Electric Warships. The flexibility of the resulting naval electric power architecture allows Electric Warships to provide power to offboard weapons and sensors, as well as forces ashore. This is the recommend route to create a technically superior Electric Naval Force.
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> In order for the Department of the Navy (DON) to realize the benefits of superior warfighting capabilities, affordability, reduced workload, commonality, and reduced logistics burden, it is necessary to centralize the responsibility for developing the enabling technologies for the Navy's future Electric Warships.

For the next several years, IPS activity concentrated on supporting the DDG 1000 program. As the basic design for the DDG 1000, IPS neared completion in late 2005, Navy interest in other applications of IPS grew. On 15 June 2006, a CNO Flag Steering Board for a Next Generation Integrated Power System (NGIPS) formed. This Flag Steering Board differed from the previous Corporate Investment Board in that it also included representatives from OPNAV and the Chief of Naval Research (CNR). This Flag Steering Board would also interact with senior industry leaders to ensure the concept had broad support.

During the summer and fall of 2006, NGIPS working groups met to develop the NGIPS concept, as well as program schedules and costs. Potential applications included a new cruiser (CGX), submarines (future SSN Flight, or SSBNX), future destroyer (DDGX), or Amphibious Warfare Ship (LSDX). Multiple, time-phased architectures, reminiscent of the IPS Baselines, were developed. Meetings with industry and the shipyards helped ensure there was a broad understanding of NGIPS goals, and enabled industry to communicate the art of the practical and possible to the government. A number of program schedule and budget options to implement NGIPS were developed. As before, these proposed budgets ranged from roughly $100 million to $300 million. While OPNAV was very interested in the technology, OPNAV was not enthusiastic in providing funding.

Due to the austere fiscal environment in early 2007, OPNAV still did not support a new large corporate investment. Consequently, focus shifted to producing a Technology Development Roadmap with the goal of minimizing new NGIPS investments by aligning already-funded investments at ONR and elsewhere to achieve the NGIPS objectives.

In 2007, the Flag Steering Board recognized that this new model for aligning existing programs required a coordination office. Hence, support grew for an Electric Ships Office (ESO) to coordinate existing activities, as well as manage programs to fill in the gaps. There was much debate as to the home organization for this office. The two options that were most favored were a program office in PEO-SHIPS, and a program office in NAVSEA SEA 05. The final consensus would be for the ESO to reside in PEO-SHIPS, but represent Electric Ship interests for all PEOs. SEA 05 would provide direct technical support. This arrangement would ensure that the ESO would engage technical authority and program authority stakeholders. Finally, on November 13, 2007, ASN(RDA) directed PEO-SHIPS to establish the Electric Ships Office. On November 30, 2007, the Electric Ships Office (PMS 320) was established.

On November 30, 2007, SEA 05, concurrent with the establishment of the ESO, issued the NGIPS Technology Development Roadmap. This roadmap was endorsed by the NGIPS Executive Steering Group (an evolution of the Flag Steering Board) on December 7, 2007. This Roadmap featured three power generation architectures (Medium Voltage AC, High Frequency AC, and Medium Voltage DC), and a zonal electrical distribution system (ZEDS) architecture based in part on the DDG 1000 Integrated Fight-Through Power (IFTP). The Roadmap defined the state of the technology, defined the need for integrated power systems, defined the power system architectures, listed technology development needs, and proposed an open-architecture-based business model. It did not define an execution plan.

In 2008, the ESO contracted Northrop Grumman Shipbuilding (both Newport News and Pascagoula yards) and General Dynamics (both Bath Iron Works and Electric Boat) to evaluate the risks associated with the NGIPS Technology Development Roadmap. In 2009, this team produced a draft NGIPS Conceptual Design Application handbook, and in 2010 produced the NGIPS *Conceptual Design Zonal Electrical Distribution System (ZEDS) Application* handbook.

The NGIPS Technology Development Roadmap also influenced the S&T initiatives at ONR, as well as within academia. The Electric Ship Research and Development Consortium (ESRDC) produced many academic papers and theses to explore the different risk areas identified in the Roadmap. At ONR, the NGIPS S&T efforts (as described on the ONR web site) concentrated on topics included in the Roadmap:

- advanced naval power systems modeling and simulation
- high density energy storage
- advanced power generation to reduce fuel consumption
- diagnostics that clearly define the fault severity and accurately locate the fault, and prognostic capability that reliably foretells the future condition of the equipment and system
- advanced power converter topologies
- application of advanced semiconductors
- power system control architectures
- power and energy management methodologies
- dynamic stability analyses

Professional societies such as ASNE, SNAME, and IEEE, provided multiple forums to advance electric warship technologies. A number of conferences and symposiums were held (see sidebar) to enable the power system and ship design communities to collaborate and share results.

The increased interest in integrated power systems also led to a number of standards activities to capture the evolving lessons learned. The first success in this area was the publishing of IEEE 1662-2008 *IEEE Guide for the Design and Application of Power Electronics in Electric Power Systems on Ships*, IEEE 1709 *Recommended Practice for 1 to 35 kV Medium Voltage DC Power Systems on Ships*, followed in 2010, and IEEE 1826 *IEEE Standard for Power Electronics Open System Interfaces in Zonal Electrical Distribution Systems Rated Above 100 kW* was approved in 2012. Updates to IEEE 45-2002 *Recommended Practice for Electric Installations on Shipboard* are currently being developed.

Within the Navy, Design Data Sheet DDS-200-1 *Calculation of Surface Ship Endurance Fuel Requirements*, and DDS 310-1 *Electric Power Load Analysis (EPLA) for Surface Ships* were updated to reflect needed changes due to the introduction of advanced electrical systems. A new DDS 200-2 *Calculation of Surface Ship Annual Energy Usage, Annual Energy Cost, and Fully Burdened Cost of Energy* was approved in 2012. A number of other component specifications and electrical power system military standards were updated.

As time progressed, the ESO increased its portfolio of component development projects. The ESO is currently developing a Hybrid Electric Drive and an Energy Storage Module (ESM) for back-fitting on existing DDG 51 class ships to improve fuel efficiency, a new Advanced Power Generation Module (APGM) for forward fit on the DDG 51 Flight III, LM2500 efficiency improvements, and an Air and Missile Defense Radar (AMDR) Power Conversion Module (PCM) for DDG 51 Flight III. The ESO is also partnering with the United Kingdom in an Advanced Electric Power and Propulsion Project to develop a power system architecture for future ships. This project agreement is currently focusing on enabling technologies for DC distributions systems.

In 2012, the ESO began an effort to update the NGIPS Technology Development Roadmap to reflect significant changes in the acquisition environment:

- The DDG 1000 program was truncated to three ships.
- The CG(X) cruiser was eliminated from the 30-year shipbuilding plan.
- The DDG(X) shifted from FY 23 to FY 31.
- Fuel savings became a higher priority for both in-service ships and new construction ships.

Technical Symposiums Supporting the Electric Warship

By Dr. Norbert Doerry

During this time period, ASNE played in important role in providing a forum for the naval engineering community to exchange ideas and lessons learned with respect to implementing an Electric Warship. In the earlier years of this period, the annual ASNE Day and the associated *Naval Engineers Journal* issue was the principal venue for conducting this interchange. The theme for ASNE Day 2007 was "Fuel Tank to Target: Building the Electric Fighting Ship.".

In 1994, the ASNE Delaware Valley Section held the first **Intelligent Ships Symposium (ISS)**. While the ISS wasn't (and isn't) uniquely focused on Electric Warship technologies, many papers addressing Electric Warship technologies have been presented. Additional Intelligent Ships Symposiums were held in the general Philadelphia area during 1996, 1999, 2001, 2003, 2005, 2007, 2009, 2011 and 2013.

Another venue was the **Engineering the Total Ship (ETS) Symposium** which was held in the greater Washington D.C. area from 1998 through 2010 on even years. Likewise, the **Electric Machines Technology Symposium (EMTS)** has been held in the Philadelphia area on even years since 2004, and has been very successful in enabling the sharing of information among the naval engineering community. The most recent EMTS was held May 20-21, 2014 in Philadelphia, PA.

In 2004, 2006 and 2008, an **Advanced Naval Propulsion Symposium**, held in the Washington D.C. area, featured many electric warship related papers. Additionally, the **IEEE Electric Ship Technologies Symposium** has been held on odd years since 2005 and has provided an outstanding opportunity for collaboration among the members of both IEEE and ASNE.

Other applicable symposiums are:

ASNE Reconfiguration and Survivability Symposium 2005, held in Atlantic Beach, FL

High-Speed/High Performance Ship and Craft Symposium 2005, held in Everett, WA

Ships & Ship System Technology (S3T) Symposium, held November 13-14, 2006 in Carderock, MD

Automation and Controls ACS 2007, held in Biloxi, MS and ACS 2010, held in Milwaukee, WI

Shipbuilding in Support of the Global War on Terrorism Symposium, held April 14-17, 2008 at the Mississippi Coast Coliseum & Convention Center

Electric Ship Design Symposium, held February 12-13, 2009, held at the National Harbor, MD

High Performance Marine Vehicles Symposium, held Nov. 9-10, 2009 in Linthicum, MD

The Center for Advanced Power Systems 10th Anniversary Celebration & Workshop "The Road Ahead for NGIPS, Energy, & Microgrid Systems 2010", held in Tallahassee, FL

The proceedings for many of these symposiums are still available from ASNE.
See *https://www.navalengineers.org/publications/symposiaproceedings/Pages/ASNELandingPage.aspx*
or contact Jared Pierce at (703) 836-6727 or jpierce@navalengineers.org

The final product, the Naval Power System (NPS) Technology Development Roadmap (TDR), was issued in April 2013. While the previous TDR was organized around different power system architectures, this TDR focused on six product areas:

- controls
- distribution
- energy storage
- electrical rotating machines
- power converters
- prime movers

This TDR made specific recommendations for technology developments. The NPS TDR recommends that in the near term (2013-2022) the Navy should focus on developing:

- an energy magazine (along with an associated advanced mission system power upgrade), to provide a multi-use energy storage to support pulse power loads, improve system stability, provide backup power, and be able to integrate with existing distribution voltages on multiple platforms
- an energy recovery system compatible with both gas turbine and diesel prime movers, to improve energy efficiency
- military-qualified, medium-voltage (4160 V), vacuum circuit breaker switchboards that will fit within the existing air circuit breaker switchboard envelopes
- a Reduced Scale Advanced Development (RSAD) Medium Voltage DC (MVDC) power distribution system, to support future destroyer and littoral combat ship designs.
- Advanced MVDC circuit protection.
- A universal ship's power management controller

The NPS TDR also recommends research into advanced conductors and advanced solid-state energy recovery.

In parallel with the ESO efforts, SEA 05, as detailed by Doerry and Moniri (2013), is updating the technical standards, specifications, design data sheets, and design criteria and practices manuals comprising the Electric Warship Technical Architecture. This technical architecture is key to the repeatable and affordable development of power systems meeting the needs of our naval forces.

High Power Radars

In the late twentieth century, the Navy was not concerned about the ballistic missile threat to its fleet. Rather, ballistic missile defense concentrated on the threat to forces within a theater (generally understood to be land forces), and to the continental United States. (MacDonald 1998) An initial capability was established through upgrades to the AEGIS weapon system and by employing the SPY-1 phased-array radar.

Radar development during the first decade of the twenty-first century focused on improving performance against aircraft and the cruise missile defense. The Dual Band Radar (DBR) consists of an X-band SPY-3 Multi-Function Radar (MFR) for horizon search, low-altitude tracking, and missile support, and an S-Band Volume Search Radar (VSR) for searching and tracking higher altitude targets. A common controller integrated these two radar with the combat system. The DBR is common to the DDG 1000 and CVN 78 designs. However, in 2010, in order to reduce cost, the Navy eliminated the VSR from the DDG 1000 design, and reallocated VSR requirements to the MFR for the three remaining ships of this class.

During the first decade of the twenty-first century, Anti-Ship Ballistic Missiles (ASBM) became a new threat to our fleet. The high terminal speed of these weapons was anticipated to exceed the capabilities of terminal defense systems. New defensive systems would be required. With current technology, radar able to detect and track the ASBM threat would be significantly larger than the SPY-1 radar, and require significantly more electrical power.

While the DBR technically-advanced shipboard radar capability, the DDG 1000 *Selected Acquisition Report (SAR)* dated December 31, 2011 stated:

> The FY 2011 President's Budget (PB) submission confirmed the reduction of the DDG 1000 Program to three ships as a result of the Future Surface Combatant Radar Hull Study in which the Navy concluded that a modified DDG 51 with an Advanced Missile Defense Radar (AMDR) is the most cost-effective solution for fleet air and missile defense requirements.

The Navy is currently developing the AMDR to provide an inherent capability for Ballistic Missile Defense, in addition to traditional air threats. The AMDR will be scalable, so that the largest achievable size that can be integrated in the DDG Flight III will be initially produced while still enabling larger arrays for future classes of ships (such as a potential Flight IV in the 2032 timeframe) to meet evolving threat capabilities. (GAO 2012)

To meet the increased power required by the Flight III for the AMDR and other combat systems modifications, the traditional 450 VAC distribution system with three 3 mw generators will be replaced with a 4160 VAC distribution system featuring three 4 mw generators. (Vandroff 2013) As the ASBM threat evolves over the coming decades, radar power levels will likely continue to increase, resulting in even more electrical power demand from the ship's power system. Integrated power systems will likely be the most affordable means to provide this power in a new design ship.

Electric Weapons

By the end of this period, electric weapons are on the verge of becoming reality. In 2014, the U.S. Navy will deploy a solid-state laser weapon on *USS Ponce* (AFSB(I) 15) that operates in the 5th Fleet area of responsibility. The Laser Weapon System (LaWS) has been demonstrated in tests against remotely-piloted aircraft and surface craft. (ONR 2013) The introduction of lasers and railguns into the fleet will realize CAPT Graham and Dr. Krolick's 1989 vision for Cluster E. While initial deployments of these weapons, such as the installation of a laser on *USS Ponce*, will likely be in non-IPS ships, the full potential of these weapons will not be realized until the Navy transitions to integrated power system-based ships; power from prime movers normally used for propulsion will be shared with the weapon systems.

FIGURE 2. Ron Flatley, left, high-energy laser area director at the Directed Energy Warfare Office, briefs Chief of Naval Research RADM Matthew Klunder on the A/N SEQ-3(XN-1) Solid State Laser-Quick Reaction Capability system's beam director and tracking mount during a tour. The Naval Surface Warfare Center Dahlgren Division's directed energy team is performing integration tests on the Potomac River Test Range in preparation for the solid-state laser's deployment aboard the Afloat Forward Staging Base (Interim) *USS Ponce* (AFSB(I)15) in the summer of 2014. (U.S. Navy photo by John F. Williams/Released).

Railguns use extremely high pulses of currents (millions of amps) to create electromagnetic forces for propelling projectiles at speeds much greater than achievable with traditional chemical propellants. Railguns offer the potential to reach targets hundreds of nautical miles away, and destroy targets with the projectile's kinetic energy. The amount of explosive propellants and projectiles can therefore be significantly reduced onboard future electric warships. Railguns can support a variety of missions, including naval gunfire support, cruise and ballistic missile defense, anti-air warfare, and defense against waterborne threats.

To date, a tactically useful railgun has not been developed. In World War I and World War II, experimental railguns were produced and tested. By 1945, projectile velocities of 1,200 m/s were achieved, but the research did not result in fielded systems. In the 1970s and 1980s, several countries, including the United States, conducted research on railgun technology. These efforts resulted in experimental railguns capable of achieving 8 MJ and greater muzzle energies. (McNab and Crawford 2004)

The current effort to develop a tactical railgun in the United States began in August 2005, with the initiation of the ONR Railgun Innovative Naval Prototype (INP). Between 2005 and 2011, Phase I of this program was able to advance railgun technology in many ways. Muzzle energy increased from 6 MJ, to a world record in excess of 32 MJ. Bore life was improved from tens of shots to hundreds of shots, pulsed power systems experienced a 2.5 times increase in energy density, and actual projectile flight bodies have been propelled on an open range. (Garnett 2012)

Phase II of the Railgun INP started in 2012. During this phase, technology is being matured for transition to an acquisition program. Technology developments include demonstrating a 10-rounds-per-minute firing rate, including thermal management for both the launcher and the pulsed power system. A prototype launcher is scheduled to be delivered to the Navy in 2014 for testing.

Summary

The period of 1989-2014 saw a symbiotic development of electric power systems and combat systems to take advantage of the greater amounts of available electrical power. These symbiotic relationships were envisioned early through the concept of Technology Clusters. While the terms Cluster A and Cluster E are no longer widely used, many of the concepts behind them were realized. Zonal electrical distribution has become the standard choice for destroyer-sized warships and larger ships, the use of medium voltage power has extended to a variety of ship types that previously employed traditional 450 VAC systems, electric drive (or hybrid electric drive) is increasingly featured in warship design, electric weapons are in development, and high-powered radar are being introduced into the fleet. Areas that have not advanced as quickly as originally envisioned in warship design include the introduction of podded and contra-rotating propulsors, elimination of long shaft lines, ship arrangements innovations, and significant producibility improvements enabled by electric drive and fuel cell viability. It remains to be seen if, and when, these technologies will be matured and introduced into the fleet.

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