An Assessment of Power Engineering Education

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Abstract

Academic power engineering programs have been in a state of decline for numerous years. During this same timeframe, technology and the application of power electronics has been growing at a rapid pace. Additionally, the utility industry has experienced a dramatic change in regulation, the end of the Cold War has reshaped U.S. defense considerations and impressed new requirements on military systems, and the U.S. economy has both soared and slumped. Integral to the success of the U.S. economy is cost-effective and reliable power generation and transmission. Electrical brown-out or black-out events result in a loss of production capability or necessitate expensive backup generation equipment; soaring utility costs mean less capital for both product development and workforce expansion.

This paper begins with an overview of the U.S. economic trends that have influenced the employment demand for power and power electronic engineers. The demand for new talent will then be evaluated in the context of the demand for more-capable and cost-effective military platforms. In particular, the technological requirements of an "Electric Warship" will underscore the need for engineering graduates, both civilian and military. Next, an assessment is offered on the current state of electric power programs within the academic community for meeting these needs. In recognition of projected technology-driven military platforms, an enhanced power engineering concentration within the electrical engineering curricula at the Naval Academy has been proposed. The paper will conclude with an overview of the selection process for curriculum topics, course sequencing, and laboratory content.

Power Engineering and the U.S. Economy

With the innovative advancements in power electronic semiconductor materials over the past few decades, the field of power engineering has expanded from the traditional focus on utility-level generation and transmission of energy to include the widespread application and use of power electronics. Meanwhile, the utility industry itself has undergone tremendous upheaval with the impact of deregulation bringing about a paradigm shift in the operational analysis, forecasting, and pricing structures of energy transfer. In fact, this change in energy management "represents the largest global industry ever to move from regulation to competition. Numbers in the United States range from $250 billion to $300 billion annually of economic impact or about 3% of the U.S. GNP."[1] These numbers are not stagnant either, due to the overwhelming reliance of the world economies on electric power. Growth within the utility sector has been projected at more than 750 GW of new generation capacity within the next ten years to be installed worldwide, requiring an investment of $500 billion.[2]

Economic competition in the electric generation marketplace has introduced widespread cost reduction efforts as well. Management strategies often have included downsizing the workforce in an effort to yield the necessary cost reductions. The end result has been an overburdened engineering workforce swept up in the demands of maintaining facility operation with minimal capacity for investigating and implementing continued technological advancements. Consequently, it has been observed that "planning, maintaining, and operating the power facilities get second consideration behind short-term financial gain. Inevitably, the penalty for this will be reduced reliability."[3]

These utility industry changes are occurring simultaneously with the explosive development of power electronic components, technologies, and topologies. Driven by the promise of more optimal operation and control, greater efficiency and use of energy, and a dramatic price versus performance ratio, the use and application of power electronics has become pervasive across all economic market sectors. For example, power electronics are commonly found in DC-DC converters, high-performance DC power supplies, AC inverters, and variable-frequency motor drives. This use of power electronics has been described as "one of the fastest changing and evolutionary technologies in electrical engineering in the recent years."[4] Some have even dubbed the end of the 20th Century as "the era of power electronics – or more truly, power electronics and information era."[4] This accolade seems justified since, "sales of power electronics equipment exceed $60 billion each year, and affect another $1 trillion in hardware electronics sales."[5]

Incredibly, during this same timeframe, "the electric power industry in the United States is facing a disquieting shortage of trained engineering personnel."[2] With not only "an immediate critical shortage of power engineers required to perform basic transmission and distribution planning and engineering"[2] but additionally, a worsening of the projected shortage of trained personnel over the next five years.[2] Thus, the burgeoning demand and opportunity for power and power electronic engineers seems apparent.

Military Platforms

The U.S. military force structure is regularly reviewed in the context of changing geopolitical threats, emerging technology, and shifting federal budget priorities. For example, the end of the Cold War has moved the U.S. Navy's focus from blue water engagement to supporting Marine Expeditionary Units and operations in the littorals. Furthermore, despite the inflow of congressional dollars to fight global terrorism, budgets remain tight for new combat platforms. As a consequence, designs must both realize economic advantages by exploiting Commercial-Off-The-Shelf (COTS) and dual-use technologies, and introduce "transformative technologies" that provide new operational capabilities to the fleet. In this context, the Navy is pursuing several initiatives that necessitate both engineering innovation from the civilian sector and a more technically capable naval crew.

One of the prime areas undergoing transformation is the naval shipboard power system. A representation of the current ship service and propulsion system for a destroyer is illustrated in Figure 1a. As shown, there are four gas turbine prime movers, with a total capacity of 78MW dedicated to propulsion, while there is an additional three gas turbines providing 10.5MW of capacity to the ship's electrical loads. The propulsion power demand follows a cubic characteristic with ship speed, and therefore at low to moderate speeds much of the 78MW capacity is unused and unavailable to other ship's systems. An Integrated Power System (IPS), as pictured in Figure 1b, converts all mechanical power into electrical power that can then be allocated as needed to propulsion, combat systems, damage control, and other shipboard systems.

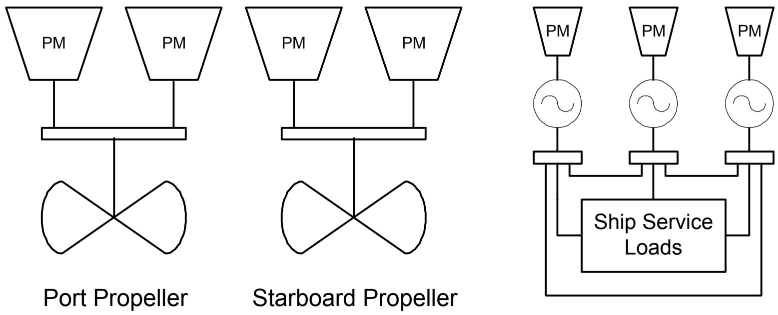

Figure 1a. Representative Current Ship Power and Propulsion System

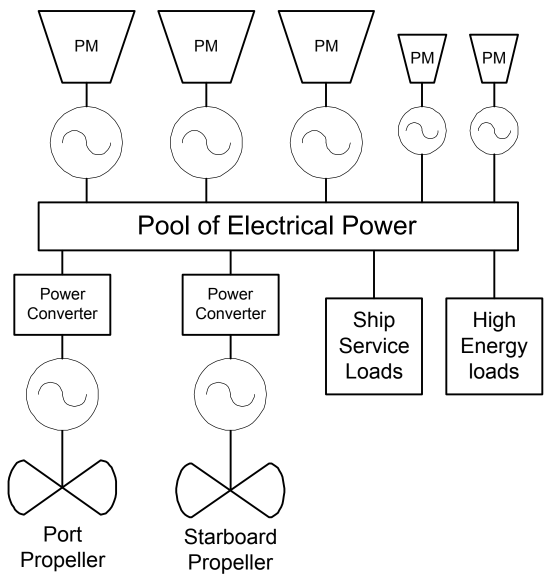

Figure 1b. Functional IPS Layout

The pool of IPS electrical capacity facilitates new types of high-energy electrical loads which were here-to-fore not feasible. In particular, new multi-megawatt weapon systems such as rail guns, lasers, and ultra wideband microwave devices can tap into the surplus ship energy and provide new offensive and defensive capabilities. In addition, electromagnetic catapults on aircraft carriers can replace steam counter-parts yielding gains in maintenance and Infra-Red (IR) signature. Finally, as other combat system electrical demands increase, only an IPS-based ship will physically accommodate the required capacity.

An IPS is predicated on transitioning ship propulsion from mechanical gears to an electric drive. The key elements of electric drive are a multi-megawatt power converter that supplies a variable-speed multi-megawatt rotating machine coupled directly to the propeller shaft (see Figure 2 for a hardware Navy prototype). The power-electronics-based converter creates an adjustable voltage source from the pool of IPS power. A version of this technology has been evolving since the late 1970's and is now regularly employed in icebreakers, cruise liners, ferries, and oil tankers. The big challenge for the U.S. Navy and civilian contractors is to address the unique military combatant requirements of shock and vibration, acoustic signature, and a highly compact design.

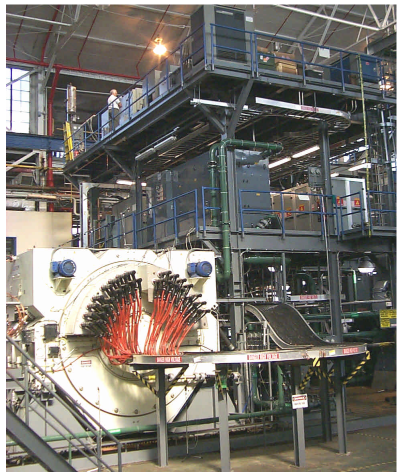

Figure 2. IPS Test Facility at NSWCCD – Philadelphia, PA

Increased operation in the littorals implies greater risk to Navy platforms and crews from shore-based attack and from mines. In several recent incidents including the USS Stark (missile attack, March 1987), the USS Samuel B. Roberts (mine, April 1988), the USS Princeton (mine, February 1991), and the USS Cole (surface explosion, October 2000), ship electrical power was compromised by either the initial damage or through the management of that damage, implying that at some point electrical power was unavailable to damage control, combat systems, and propulsion auxiliaries (see Figure 3). The design of future shipboard distribution systems must guarantee enhanced survivability as ships more frequently support Marine Expeditionary Units off shore.

Figure 3. Battle Damage Photos USS Cole (left) and USS Stark (right)

In advance of this goal, the U.S. Navy is investigating a power-electronics-based DC zonal electric distribution system. A portion of one such architecture is illustrated in Figure 4. As shown, the AC output voltage of one of the ship's generators is converted to DC and distributed along either a port or starboard bus. The ship's electrical loads are divided into zones that are delineated by watertight compartments. DC-DC converters couple into a zone from either bus to provide a primary and an alternate power path for vital systems. The DC-DC converter buffers the main bus power from the inter-zonal loads, thereby providing greater fault isolation than what is achievable in the current AC zonal system. Diode-auctioneering allows for power to be rapidly switched from one bus to the other to enhance the continuity of electrical service to vital loads. Further downstream, DC-AC inverters then process the inter-zonal power to create the flavor of AC required by the loads. Significant engineering strides are required to produce very power-dense converters that can be stably interconnected in the variety of configurations that battle situations may impose. Engineers must develop control strategies that enable the system to be self-healing, gracefully degrade operation, and maximize continuity of power to critical loads.

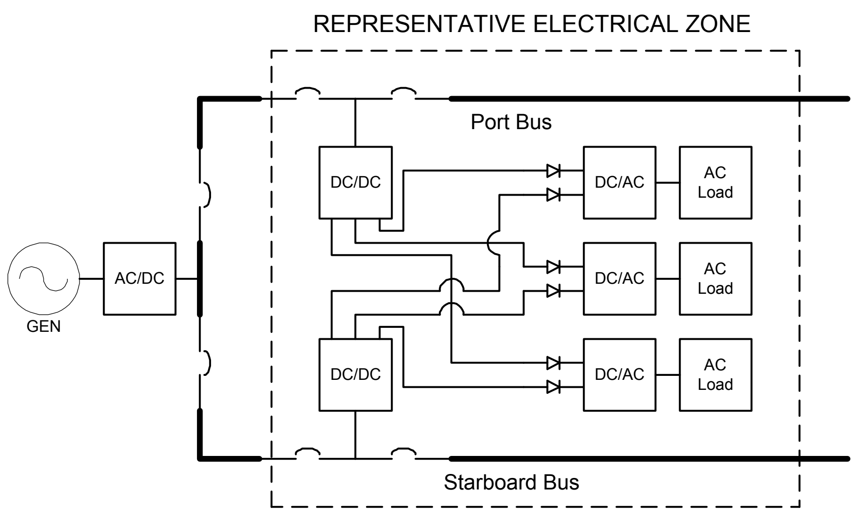

Figure 4. Portion of DC Zonal Electric Distribution System

In addition to IPS, electric drive, and new advanced electrical loads and distribution systems, the Navy is exploring further applications where power electronic advances may be exploited. A current surface combatant has hundreds of motors that are operated at fixed or dual speed. Many of these applications can realize substantial efficiency gains by employing a variable-speed drive. For example, the Heating Ventilation and Air Conditioning (HVAC) system can transition from the mechanical to the electrical control of flow rates as is commonly done now in terrestrial installations. The common thread running through all of these emerging naval applications are the requirements of a more technically competent naval crew and solutions to some challenging technical hurdles from the civilian marine power engineering community.

Power Engineering and Academia

Ironically, as both the civilian and military sectors are showing a rapid growth in the demand for expertise in power systems, statistics have shown that student enrollment within the field of power engineering has deteriorated over the past several decades.[2] This trend has positioned many universities to allow their programs in this field to dwindle as the aging faculty with proficiency in power systems transition into retirement. These vacated faculty positions are frequently filled with people having experience in what is perceived to be more desirable areas. Often, the management and allocation of faculty resources in this manner is driven by the statistics in student enrollment and choice of major. Thus, it appears as though the proverbial 'catch-22' situation exists. This dilemma is not isolated to the U.S., but has impacted other countries as well. During a recent panel discussion on the global state of power education, the observation was made that "large numbers of American universities have eliminated Power Engineering from their curricula"[6] which "has produced a crisis in power engineering education."[6] Moreover, it seems as though this declining trend is also affecting Germany and the United Kingdom.[6]

Various initiatives have been launched to break this cycle and reverse these trends. Opportunity exists to revamp and retool the pedagogical approach traditionally used to teach power systems to include simulation and visualization software techniques, partnering more closely with industry to provide both realistic project activity as well as continued education options for the existing workforce, and to utilize alternative classroom delivery techniques and mechanisms. The National Science Foundation has identified the need for innovation in this area and has aggressively sponsored research and development activities to address and remedy this situation.[7-10]

Curriculum Section

Recognizing the demand for power engineering expertise and the current pool of available talent, the U.S. Naval Academy has embarked on a path to create a power systems track within the electrical engineering major. The goals of the proposed track are to educate junior naval officers in the operation, analysis and design of shipboard power and power electronic systems; to prepare them for graduate studies in power engineering; and to facilitate any future transition into the civilian power engineering sector. In order to accommodate the structure of the current EE program which consists of a sequence of required core courses followed by a selection of specialized "track" courses, the authors proposed a modest modification of the core and the addition of three new power systems track courses. As an integral part of this effort, a modern power laboratory is being designed and is anticipated to support a studio-based teaching approach.

In implementing the three-course sequence, the authors sought to efficiently synthesize the machinery, power electronics, and systems topics into a coherent instructional narrative. The starting point was in identifying the top-level sequencing of topics. Here the authors decided on a junior-level power electronics course, followed by a senior-level machinery course, and a capstone shipboard power system course. It was deemed desirable that there be some overlap between courses to underscore the interconnectivity of topics, the multi-EE-interdisciplinary nature of power engineering, and to provide new perspectives on old material. For instance, it is intended that 3-phase inverters be introduced in the power electronics course and then applied to the control of AC drives in the machinery course. Generators, motors and converters would then all be considered from a systems perspective in the capstone course. The authors also find it important that there be a basic story-board system that threads its way through the sequence. One such system is illustrated in Figure 5. This motivational system possesses components that are generic to many applications and thus the student can immediately tie the component analysis to a system application. Finally, the authors sought to make the sequence highly navy relevant to meet the objective of having a well-prepared incoming officer corps.

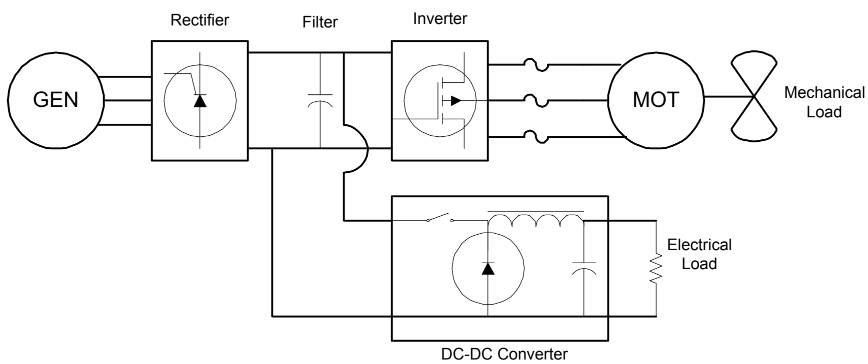

Figure 5. Thematic System for Power Sequence

With the stated goals above, the authors moved to identifying course content. A broad list of power system topics was assembled upon reviewing textbooks, other reputable undergraduate power system programs, and current and future Navy power system applications. At this point, the authors stopped and created a list of student skills that they wanted emphasized in the curriculum. The following is what emerged: a strong theoretical foundation, modeling skills, ability to perform analytical calculations, exposure to simulation and development tools, competence in the use of instrumentation and test equipment, experience in design and prototyping, and an understanding of applications. This comprehensive skill set juxtaposed with the admissible course topics presented the not uncommon choice of depth versus breadth. In order to have some overlap, interject Navy-relevant applications, engage in meaningful design and laboratory investigation, and provide analytical skills that are maximally portable to future problems, certain converter and machine topologies and power system analysis techniques had to be sacrificed.

The junior-level power electronics course will cover the following topics: the characteristics and design relationships of basic converters (rectifiers, inverters, and dc-dc converters), device characteristics (MOSFET, IGBT, thyristor, GCT) and practical considerations (drivers, snubbers, circuit layout), and DC motor control as a case study. The senior-level machinery class will emphasize the following topics: general coupled-circuit and field energy approach to analyzing electromechanical systems, equivalent circuits (induction and synchronous machines), induction machine drives, generator-rectifier characteristics, and the design of special machines for marine propulsion. Finally, the senior-level ship power systems course will introduce the following topics: per unit analysis, current architectures, fault analysis, power system control and protection, integrated power systems and electric drive, advanced distribution systems, and new technologies (i.e., fuel cells, super-conducting machinery, multi-level inverters). As may be apparent, the "systems" course requires a good student background in both power converters and rotating machinery. This overall selection of topics is predicated on the core Circuits II course introducing three-phase circuits and power calculations, DC machines, and single and three-phase transformers.

The course implementation is closely tied to the design of a Power Systems laboratory. The goal of the lab is to provide the following functionality: exploration of fundamental principles, course prototyping and integrated simulation projects, controller rapid-prototyping capability, and industrial and navy demonstrators. It was also deemed attractive to design the lab layout to accommodate studio teaching so that the lab-lecture time block is an integrated experience. The prototyping capability must also support student senior design projects, student senior thesis projects (called Trident projects), and on-site faculty research. A vibrant, utilized laboratory is viewed as key to capturing student interest and growing a new electrical engineering track.

The demonstrators are intended to extend the student exposure from instructional-grade equipment to commercial grade and in the process provide some experience in component sizing, packaging, nameplates, and industrial performance. It is intended that the development of these demonstrators will also lead to field trips to Navy and industrial facilities to provide student interaction with practicing engineers.

Currently, the curriculum innovation is supported by U.S. Naval Academy funds and by a proposal funded by the Office of Naval Research (ONR). The ONR effort comes under the National Naval Responsibility (NNR) initiative which in part seeks to develop education strategies to produce more and more capable marine engineering students. Some of the participants in the NNR program are the U.S. Naval Academy, MIT, Purdue University, the University of Missouri at Rolla, the Naval Postgraduate School, and the University of Wisconsin at Milwaukee.

To summarize, the goal of the U.S. Naval Academy power systems track is to provide the Navy with graduates who are creative problem solvers, possess engineering sense and hands-on experience, who understand the limits and practical applications of technology, and who can competently manage complex naval electronic and power systems. The graduates must also then be adequately prepared to transition from the fleet to the industrial sector and provide leadership and experience in improving the design, fabrication, operation, maintenance, acquisition, and training of complex Department of Defense (DoD) and commercial systems.

Conclusion

This paper is an effort to highlight the authors' perspective and concern on the present state of power engineering in the United States. These concerns have a broad foundational basis when viewed in context with both the civilian and military need for power engineering and the state of academia to service those needs. The U.S. Naval Academy is responding to this situation by introducing and developing an EE concentration focused on power systems. Hopefully, the academic community can review their role in this matter and put forth additional effort to revitalize and rejuvenate the power engineering discipline.

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