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A NOVEL POWER SYSTEMS PROGRAM AT THE NAVAL POSTGRADUATE SCHOOL

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***Abstract*--The Power Systems program at the Naval Postgraduate School is a unique academic endeavor which seeks to both educate Navy officers in relevant advanced technologies and to complement the research efforts on-going at the government laboratories. The move toward incorporating more-electric technology into naval combatant shipboard power systems and the requisite analysis of such finite-inertia, stiffly-connected systems have driven the development of a program that intermixes power electronics, electric machines, and microprocessors. Through work emphasizing analysis, hands-on hardware investigation and simulation, the students are exposed to the diverse issues encountered in power system research. The students are also presented unique opportunities to interact on-site with various government laboratory sponsors to further draw the connection between theory and hardware implementation.**

Keywords--power engineering education, modeling, simulation and power laboratory.

I. INTRODUCTION

The Naval Postgraduate School (NPS) is a unique academic institution whose primary mission is to increase the combat effectiveness of the Navy and Marine Corps. Through the use of specially-tailored programs not available at other educational institutions, the faculty at NPS seek to prepare U.S. officers from all branches of the uniform services to introduce and utilize advanced technologies relevant to the unique requirements of the Department of Defense. The faculty, the majority of whom are civilians, are actively engaged together with the government laboratories in naval and maritime research which facilitates innovation and technological change in the Navy.

The remarkable increase in microprocessor technology coupled with the development of high-power semiconductor devices has fueled industry-wide interest in employing electromechanical actuators and power electronic converters in terrestrial, aerospace, and marine systems [1]-[4]. An example of such a move toward more-electric technology is the investigation by the Naval Surface Warfare Center investigating into an Integrated Power System (IPS) for twenty-first century naval combatant vessels. The proposed system incorporates a DC Zonal Electrical Distribution System (DC ZEDS) as illustrated in Fig. 1 [5]-[7]. Another example is the Power Electronic Building Block program sponsored by the Office of Naval Research (ONR). The PEBB research goal is to develop a new power semiconductor module that has vastly improved characteristics over current-technology devices, such as current density, voltage capability and speed. The thrust of this effort is to reduce cost and weight while dramatically increasing reliability and modularity.

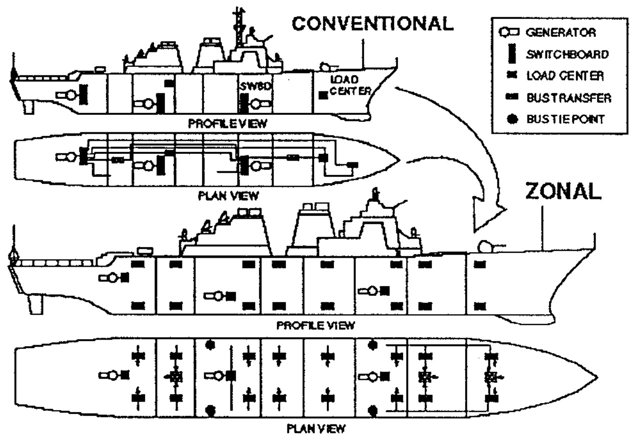

Fig. 1. DC Zonal Electric Distribution System (DC ZEDS)

In an era of shrinking defense budgets, it is vital for military research initiatives to reduce production costs and raise efficiency standards. For instance, the advantages of DC ZEDS include zonal fight through survivability, enhanced flexibility and producibility, increased reliability for combat systems by maximizing continuity of power, improved management of power, decreased weight, and acquisition cost savings. In response to this technological push and the growing need for Naval officers to be schooled in this advancing area, NPS established a Power Systems Engineering program within the School of Electrical Engineering. This Power Systems program also supports the Total Ships Systems Engineering effort which is an interdisciplinary effort toward educating the officers from a systems-level approach. The electrical engineering curriculum offers formal concentrations in: Communication Systems, Computer Systems, Guidance, Navigation and

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Control Systems, Electromagnetic Systems, Signal Processing Systems and Power Systems. The curriculum presently consists of approximately 120 students of which one-fifth are in the Power Systems tract or are currently enrolled in Power Systems courses. The department is supported by approximately 45 faculty members. To satisfy the requirements for a master's degree, a student must complete 52 quarter credit hours of graduate level work and must present an acceptable thesis for a minimum of 16 credit hours.

The Power Systems program at NPS offers a broad, balanced approach to power engineering which emphasizes integrating classroom instruction together with hardware experimentation, computer simulation, and research projects. By maintaining a close affiliation with Navy research labs, the contents of the courses are kept relevant and the students are motivated by timely issues. Owing to the continued shift in industrial and government-sector research interests, a wide variety of approaches to power engineering education have been adopted and presented in the literature [8]-[15]. This paper seeks to augment that selection by introducing the structure and mission of the unique Power Systems program at NPS.

II. PROGRAM STRUCTURE

For a student to excel in the multi-disciplinary field of power engineering, a program must offer the fundamentals of circuits, electromagnetics, semiconductors, power electronics, electric machines, and electric drives as well as controls, microprocessors, and numerical methods. Structuring a program which intermixes these diverse topics, the faculty has emphasized an approach that merges theoretical course work, laboratory experimentation, and computer simulation and design. Since the student is required to complete a thesis to receive a master's degree in Engineering, this program prepares the student with maximum flexibility to engage in hardware, software [16], and/or theoretical research.

To implement such a comprehensive approach, the faculty developed a power systems laboratory stressing both hardware and software capability. The five lab benches are stocked with AC and DC motors, transformers and variacs, AC and DC variable power supplies, power electronic converters, scopes and probes, data acquisition capacity, and a variety of analog and digital discrete components. Within the lab, the students have access to several networked SPARC workstations, as well as 486 PCs, which all have data processing capability. For simulation and analysis, the Advanced Continuous Simulation Language (ACSL) [17], SIMULINK [18], MATLAB, Saber [19] and PSPICE are made available to each student through the computer network. By emphasizing a hands-on approach to education through electronic and computer hardware, the professors have found that students are better able to appreciate and extend further the theoretical information presented in class.

Being a new area at the school, the Power Systems program presently consists of five regularly scheduled courses summarized in Table 1. When possible, the faculty will bring on-line several additional courses which are briefly introduced in Section IV of this paper. Presently, the students are encouraged to investigate additional advanced topics through directed study courses and thesis research. Since not all officers entering the program have an undergraduate degree in engineering, the usual undergraduate courses in circuits, transistors, fields, and control provide the foundation for graduate study. The graduate electrical engineering program, leading to the MSEE degree, is accredited as an Electrical Engineering Program at the advanced level by the Engineering Accreditation Commission of the Accreditation Board for Engineering and Technology (ABET).

As part of the 27 credits of advanced electrical engineering course work, a student in the Power Systems option typically enrolls in the following course offerings:

TABLE 1.
Summary of Graduate Courses Presently Offered.

Course Title	Lecture hr/wk	Lab hr/wk
Electrical Machinery Theory	4	2
Solid State Power Conversion	3	2
Advance Electrical Machinery Theory	4	2
Advance Solid State Power Conversion	4	1
Electric Power Engineering	3	1

A. Electrical Machinery Theory (EC3130)

This course provides an introduction to the analysis of electromechanical devices using a magnetically-coupled circuits approach. The course includes explicit derivations of the governing equations for transformers, DC machines, induction machines and synchronous machines. In addition, equivalent steady-state circuits are developed, reference frame theory is applied to the AC machines, and the student is introduced to the basics of machine simulation as required in shipboard electric drive analysis.

Laboratory Work

Each student is required to complete a set of tutorials structured to introduce the basic issues relevant to power system simulation. Once the student is introduced to the governing equations of the various components, an emphasis is placed on the student then being able to structure an appropriate digital simulation. The electromechanical device experiments in the EC3130 laboratory use a diverse selection of LabVolt machines and data acquisition equipment. Experiments include:

- Introduction to the Universal Motor
- Power Transformer Characteristics
- DC Machine Characteristics
- Automatic Starting and Speed Control of DC Machines
- Split-Phase and Capacitor-Start Motor Characteristics
- Capacitor-Run Motor Characteristics

B. Solid State Power Conversion (EC3150)

In this course, a variety of solid-state power conversion circuit topologies found in Naval shipboard power systems are examined. The conversion circuits and techniques are analyzed, tested in hardware, and in some cases simulated. An overview of commonly used switches is taught. Topics include:

- *AC-to-DC* - Controlled Rectifiers: Half and full-wave rectifiers in both single and polyphase configurations are analyzed with resistive and inductive loads. The DC load line is also detailed so that critical inductance values are resolved.
- *AC-to-AC* - Phase Control: Integral and phase control with resistive and inductive loads are analyzed to examine currents, voltages, power factor and harmonics.
- *DC-to-DC* - Converters: The buck, boost, buck-boost, forward and flyback converters in both continuous and discontinuous modes are studied and analyzed in detail. Component size selection based on current and voltage ratings is also presented.
- *DC-to-AC* - Inverters: Half-bridge, full-bridge and polyphase inverters are presented. Different control algorithms (square, 6-pulse, PWM, sine-PWM, etc.) are analyzed to examine their effects on output voltage control and harmonic content.

Laboratory Work

The power electronics laboratory experiments for EC3150 combine a number of InverPower electronic modules together with standard monitoring and data recording equipment. The experiment topics include:

- Single and Three-Phase Half-Wave Controlled Rectifiers
- Single and Three-Phase Full-Wave Controlled Rectifiers
- DC Load Line Using Single and Three-Phase Full-Wave Controlled Rectifiers
- Single and Three-Phase AC Voltage Control
- Buck, Boost and Buck-Boost Choppers
- Three-Phase Voltage Source Inverters with 6-Pulse and SPWM Control

C. Advanced Electrical Machinery Systems (EC4130)

This course introduces the advanced analysis of detailed and reduced-order representations of shipboard electric machinery and power electronic drives. In addition, the officers are exposed to the fundamentals of vector control, the modeling and control of DC link systems, the modeling and control of current source inverter systems, and the design of constant flux AC machine drives. The course includes specialty topics such as simulating magnetic saturation and open-phase fault conditions, the resolution of algebraic loops in reduced-order systems, and the detailed simulation of stiffly-connected systems. Upon developing linearized models, projects incorporate the basics of linear control theory as applied to electric drives. Simulation projects include:

- 3-Phase Induction Machine
- Induction Machine Control System
- 3-Phase Reluctance Machine
- Shipboard Power System
- Representative Shipboard Electric Drive

Laboratory Work

Using equipment similar to that described in EC3130, the laboratory projects in EC4130 continue introducing the Naval officers to practical device characteristics. Experiments include:

- 3-Phase Induction Machine Parameters
- Synchronous Machine Starting Characteristics
- Power Factor Control of a 3-Phase Synchronous Machine
- Synchronizing an Alternator to the Electric Power Grid
- Slip Energy Recovery System

D. Advanced Solid State Power Conversion (EC4150)

This course concentrates on the design and analysis of modern solid-state power electronic circuits compatible with present and future ship electric power systems.

- *Components* - Non-ideal aspects of both passive and active components are discussed. Practical design techniques are emphasized, including stacking and paralleling to meet voltage and current specifications.
- *Auxiliary Device Design* - Various solid-state protection schemes are presented. The proper sizing of snubber components, including MOVs, is stressed in addition to the determination of cooling and heat sink requirements.
- *Modeling & Simulation* - The open and closed-loop dynamic performance of various converters are analyzed using state-space averaged models and pole placement techniques.

- *Resonant Converters* - Zero-voltage and/or zero-current switching converters are described concentrating on load, switch, and DC link resonant converters.
- *APLC* - Various active power line conditioners which monitor voltage, current, or both are analyzed. The suppression of current harmonics is highlighted.
- *Current Research* - Relevant research from IEEE transaction journals is presented focusing on material applicable to the power electronic sequence.

Laboratory Work

Several DC-DC converter topologies are evaluated in the power laboratory emphasizing the effects of non-ideal components, transient waveshapes, and efficiency. To compliment the resonant converter analysis presented in class, four different topologies are built and their characteristics examined in the laboratory. In order to study a representative APLC, an in-house unit, consisting of a "soft" power bus containing both linear and nonlinear loads, is assembled and a closed-loop control system is implemented using the "point of connection" voltage waveform. The main thrust of the laboratory portion of the course, however, is to have the students design, analyze, model, build, test, debug, and improve upon a particular type of converter selected by the instructor. By providing the students with an open-ended set of specifications, the instructor emphasizes the real-world issues involved in making a system work.

E. Electrical Power Engineering

This course provides an overview of the principles, broad-based concepts, and tradeoffs implicit to the design of shipboard electric power systems. Emphasizing advanced electrical power system configurations for ship service and ship propulsion, the theory necessary to understand complex component interactions is formulated and discussed.
Topics include:

- *Three-Phase Power* - The balanced and unbalanced delta and wye-configured three-phase systems are analyzed in detail.
- *Converters* - The different topologies used for converting AC-to-DC, AC-to-AC, DC-to-DC, and DC-to-AC are presented.
- *Modeling & Simulation* - State-space averaged models are developed and used in dynamic studies.
- *Future Shipboard Power* - In order to reflect the emphasis on a more-electric Navy, the advantages of using power electronic conversion, rather than motor-generator sets, is introduced and discussed. In addition, future concepts relevant to propulsion and distribution are highlighted.

Laboratory Work

The laboratory experiments cover three-phase power sources and loads, converters and inverters, and end-to-end power system construction. The final lab involves the connection of a three-phase source to a six-pulse rectifier followed by a DC-DC converter and an inverter-driven induction machine.

III. PROGRAM RESEARCH

With the active-duty officers at NPS already receiving full salary benefits, there are no research-assistant costs for directed in-house research. As a result, proposals may be drafted with fewer direct expenses for the available manpower hours. Since students are required to complete a master's thesis to satisfy the graduation requirements, they actively pursue interesting and timely research opportunities. In this section, a few representative research projects are discussed, highlighting the breadth and sophistication of the student involvement.

The DC ZED system architecture employs a port and starboard DC bus. The ship electrical systems are divided into individual zones which are connected to both DC busses. In order to supply the lower-voltage requirements within the zone, the bus voltage is reduced by a controlled DC-DC converter. The converter is controlled to maintain the zone voltage constant in the presence of disturbances at the bus and electrical transients within the zone. A thesis project involved building a low-power prototype of the DC distribution system in the power systems lab, developing an end-to-end SIMULINK model of the system, validating the model against the hardware, then designing and implementing a variety of hardware-in-the-loop control topologies for the DC-DC converter [20]. The project emphasized the validity of the digital simulation, the utility of designing controllers using the simulation, and the ease of implementing and verifying the control using a dSPACE DSP board and accompanying software [21]. Such a project demonstrates the interdisciplinary nature and practical applications stressed in the power program.

Power systems onboard marine vessels are unique in that they are finite-inertia and stiffly-connected; that is, infinite-bus assumptions are invalid and the components are interconnected through short tie-lines. A short tie-line assumption leads to a connection incompatibility between standard models of network components. The development of nonstandard, reformulated component models by Mayer [22] offers an alternative approach to introducing auxiliary network components. A thesis project at NPS investigated the application of a differential algebraic solver available in ACSL to a detailed representation of a shipboard power system [23]. The results contrasted the modularity, flexibility, and accuracy of this method with the methods presented in the literature. Such an effort supports the simulation work presently being performed at the Naval Surface Warfare Center (NSWC).

An effort has been made at NPS to establish a close link between the research labs and the thesis work. For instance, a recent thesis investigated the hardware implementation of a multi-loop DC-DC converter control [24]. The student was able to travel to NSWC and perform the hardware development on-site. In addition to gaining the experience of working on an engineering team, the student demonstrated and validated his control hardware using the actual in-lab DC-DC converter. This arrangement has been found to be mutually beneficial to student and sponsor.

Thesis topics in progress include active power line conditioner techniques, the study of stability issues in a DC-distribution system, the application of variable speed drives to the control of centrifugal pumps, and an autonomous electric-vehicle propulsion simulation package. An emphasis is placed on anticipating the needs of the twenty-first century Navy and developing innovative solutions..

IV. FUTURE INITIATIVES

Anticipating future growth in interest in the area and research opportunities, the faculty is actively planning to expand the course offerings, the laboratory facilities, and the range of research endeavors. In particular, courses in load flow, power quality, and advanced electric drives are being developed. These courses, emphasizing the unique engineering issues common to shipboard power systems, will build upon those courses described in this document.

Furthering the power laboratory capability is vital to meeting future research tasks and challenging the abilities of subsequent classes of students. The available power to the lab must be expanded to levels commensurate with existing Navy technology. In order to extend the prototyping facility, the faculty foresees upgrading the component equipment to include more industry-grade electric machines and power converter technology. In addition, the hardware-in-the-loop capabilities of the laboratory are planned to be expanded and used to investigate a variety of application hardware and control strategies.

In an effort to forward the Navy's emphasis on dual-use technology, the faculty will actively pursue civilian research sponsors who share common interests. This venture seeks to draw a nexus between the specific needs of maritime systems to that of civilian systems attempting to compete in the world market.

V. CONCLUSION

The Power Systems program at the Naval Postgraduate School is a unique academic endeavor which seeks to both educate Navy officers in the advanced technologies relevant to the Navy and to compliment the research efforts on-going at the government laboratories. As such, the program differs greatly from most conventional power system programs which emphasize terrestrial systems. It has also been illustrated in this paper that the program emphasizes a multifaceted approach to education including theoretical rigors, hands-on hardware investigation, and simulation efforts which stress design and control. Several representative thesis projects have been introduced, demonstrating the synergy between Naval research concerns and the thesis focus.

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VII. BIOGRAPHIES

Robert W. Ashton graduated from Virginia Polytechnic Institute with a B.S.E.E. in 1982. He worked for Unisys Corporation as a Component Engineer until returning to school in 1986. He received his M.S.E.E. in 1989 from Worcester Polytechnic Institute. He earned a Ph.D.. in the area of power electronics while a fellow with Northeast Utilities in Connecticut. He currently holds the position of Assistant Professor in the Department of Electrical and Computer Engineering at the Naval Postgraduate School in Monterey, CA.

John G. Ciezki graduated from Purdue University in 1993 with a Ph.D. in the area of Power Systems. He has done extensive research with P. C. Krause and Associates while working toward his degree at Purdue. Following post doctorate work at Purdue, he joined the staff at the Naval Postgraduate School in 1994 as an Assistant Professor in the area of Power Systems.