GRADUATE EDUCATION FOR PULSE POWER SYSTEMS

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ABSTRACT

This paper describes the pulse power curriculum. It begins with a description of a pulse power system. Curriculum development is discussed, and the curriculum is described. Unique features include a required thesis, and a very applications oriented design course. Supporting activities of other agencies are also described.

INTRODUCTION

In the early 1970's, the Air Force projected the need for airborne power systems providing power and voltages significantly higher than any present systems. Studies conducted at that time indicated that the greatest benefit could be derived from development of advanced components to meet the stringent weight and volume constraints of airborne systems. Systems developments were to be delayed until some successes were evident from the component development programs. A large group of research scientists and engineers was assigned to these component development programs. As the programs began to yield successes, the emphasis began to shift toward systems development; however, the same research scientists and engineers remained involved with the programs. As systems development evolved, the need for a more systems oriented engineering group became evident.

Although a number of universities offer graduate courses related to pulse power systems, programs emphasizing the complete pulse power system have not been available. During 1978 the Air Force Weapons Laboratory asked the Air Force Institute of Technology to develop a graduate electrical engineering curriculum with specialization in pulse power systems. A curriculum development committee, which included laboratory personnel, was formed, and a curriculum was developed. The first group of students entered the program in June 1979 and graduated in December 1980.

DESCRIPTION OF PULSE POWER SYSTEM

Figure 1 shows, in block diagram form, the possible components of a pulse power system and their positions with respect to each other in the power chain. The actual system configuration is dictated by the mission requirements and the type of load to be supplied. Blocks containing asterisks are the areas most heavily emphasized in the AFIT Pulse Power Curriculum.

A typical system contains a prime source of electrical power, power conditioning components, and if required for a pulsed load, energy storage components and pulse forming networks. The prime power sources convert potential chemical energy to electrical energy. Power conditioning components are used to transform the electrical energy to the specific form needed by either the load or energy storage devices. The energy storage components accept electrical energy over a fairly long period of time, and are discharged very quickly into the pulse forming network. Pulse widths of a few μsec, with rise times of a few nsec are typical. The pulse forming network shapes the output and transforms it to the proper voltage level. Switches are used to control the charge-discharge cycles. The components shown in Figure 1 are discussed in greater detail in this section.

Figure 1 shows four different prime power sources. Fuel cells and magnetohydrodynamic (MHD) generators are direct energy conversion devices. Batteries are basically energy storage devices which can be discharged at limited rates. All three of these sources produce unipolarity, or direct, voltage at their terminals. When connected to a load these sources produce direct current. None of the three is a serious candidate for pulse power systems due to their large volumes and high weights.

Turbine-generator combinations are presently being developed as the prime power source. These consist of propellant tanks and their associated pumps, a combustor or gas generator, an impulse turbine, and a rotating electrical generator. The combustor is, in fact, a rocket engine which converts the propellant to gas at very high temperatures and pressures. This high energy gas is expanded through a very high speed (15,000-30,000 RPM) impulse turbine which converts the input energy to torque. The torque is applied to a lightweight generator ($\approx$ 0.1 pounds/kilowatt) which converts the torque to electrical energy. These generators tend to be low voltage machines in the range of 1 KV line-to-line if they are iron cored; however, a non-iron cored superconducting machine presently under development generates 30 KV line-to-line. All rotating generators under development for pulse power systems produce alternating voltage at their terminals.

The electrical outputs of any of the prime power sources will rarely be in a form that is directly usable. The load normally requires higher voltages than can be directly generated, and many loads require high constant voltage. Therefore, some form of power conditioning is normally required. The two power conditioning units shown in Figure 1 are the transformer/rectifier and the inverter/converter; however, various combinations of these units are possible as determined by the particular requirements.

The transformer/rectifier is used to increase the voltage from an alternating voltage source, and then rectify the high voltage into direct voltage if required. If the load requires alternating voltage, the rectifier is deleted from the power conditioner. The transformers are very lightweight units made possible by operation at high frequencies and employment of very advanced cooling techniques. If a rectifier is required it will be solid state diodes if voltage control can be achieved at the generator. Voltage control can be achieved within the power conditioner by using silicon controlled rectifiers (SCR) with phase control.

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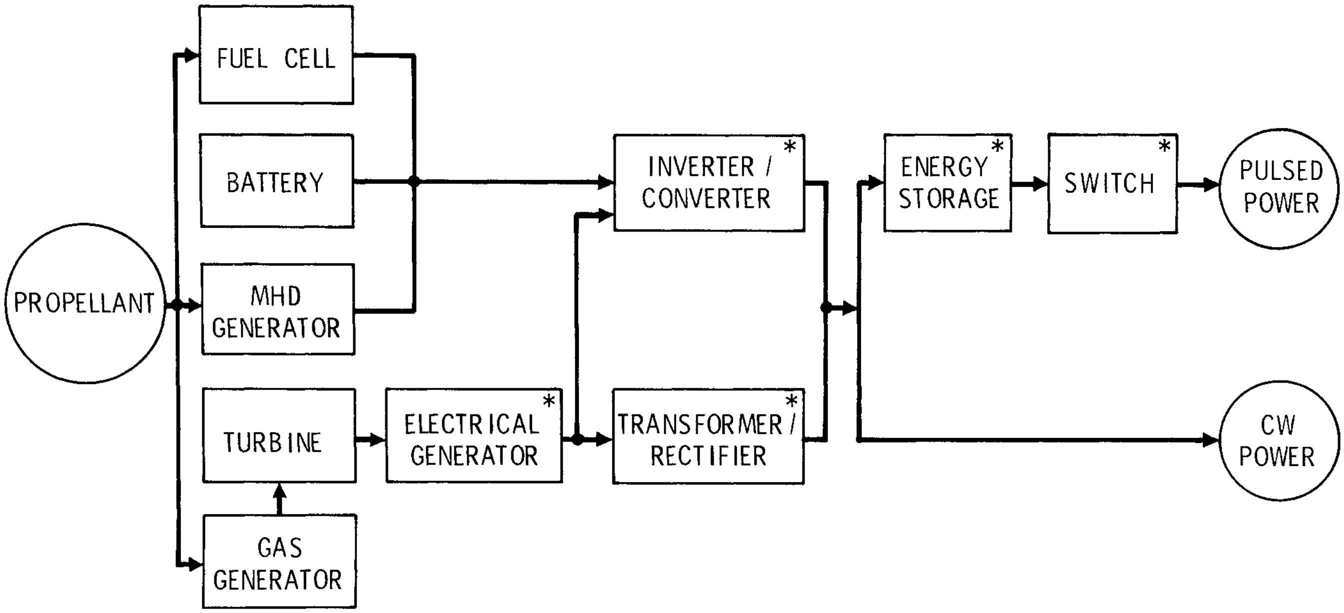

Figure 1. Block Diagram of Possible Pulse Power System Configurations

A significant weight savings can be achieved by operating transformers at very high frequencies (5 KHz-15KHz). This is one purpose of the inverter/converter unit. The other purpose is to provide a means for increasing the voltage from the dc sources. If a low frequency rotating generator is used as the prime power source, the output can be rectified to dc and applied to the input of a high frequency inverter. The inverter converts the direct voltage input to a very high frequency alternating voltage which is then stepped up to a higher voltage by a very high frequency transformer. If the prime power is direct, the input rectifier is not needed. The output from the transformer is rectified since the frequency is too high to be usable at the load.

The conditioned power from the rectifier units can be applied directly to the continuous (CW) load. The pulsed load requires further conditioning of the power in the energy storage and switching units. Energy storage units serve two basic functions: provide for storage of energy between pulses so the system can be sized for an average power level, and provide a constant load to the power conditioners thereby isolating the power supply from the pulsed load. The latter function is essential to minimize power and torque pulsations in the prime power supply which cause extreme vibration. Energy can be stored either inductively or capacitively at the average power level. The energy stores are discharged at very high power levels with specified pulse widths and pulse repetition rates. All charging and discharging is controlled by switches such as SCR's or thyratrons. The switches normally route the energy through pulse-forming-networks to a pulse transformer. The output of the pulse transformer is a very high voltage (tens of kilovolts), short time pulse (a few μseconds) that is applied directly to the load.

In addition to the units shown in Figure 1 is an auxilliary power channel that is required to control the load. This channel will also contain power conditioning units, but at a much lower power level than the main channel. Also not shown is the control system for the entire power unit. As presently envisioned, the controls will be entirely digital with a minicomputer base. This approach to control requires interfacing logic level signals to very high voltage and current elements, and the development of control algorithms to overcome the limitations of sampled data systems. The fact that the entire system must be small enough and light enough to be mounted in a flight vehicle merely adds to the challenge.

CURRICULUM DEVELOPMENT

Technology development and component development work for pulse power systems has been underway for a number of years. Most of this work has been done by specialists in a specific technology area. As work proceeds toward complete systems development there is an increasing need to involve engineers who have a better understanding of the systems aspects. AFIT was asked in 1978 to develop a graduate program to educate these systems oriented engineers, and to start the first group of students through the program in the Summer of 1979.

Curriculum development began during the Summer of 1978 with the formation of a curriculum development committee that included members of the AFIT faculty, and scientists and engineers from the Air Force Weapons Laboratory and the Aero Propulsion Laboratory. The committee decided that the engineers responsible for advanced development of pulse power systems need a rather broad background in electrical engineering with additional specialization in energy conversion and storage, high energy switching, high energy electric and magnetic fields, and digital control systems. This engineer must also understand the interactions of the various components of the pulse power systems to the extent that the graduate can model the entire system to determine design feasibility, and write detailed design and development specifications.

The actual curriculum development was done using the Instructional Systems Development approach. Using the goals set forth above, the committee began filling in the specific topics necessary to progress from a

BSEE to an MSEE with emphasis on Pulse Power Systems. This part of the curriculum development was done primarily by the AFIT faculty with guidance from using organizations. The final program contains 82 Quarter Hours of work broken into three basic course sequences, a required thesis, and broadening courses. The program requires 18 months (six academic quarters) to complete. One full quarter is devoted to thesis research, and the Committee strongly recommended that the students do their research at a Department of Defense Research Laboratory.

The basic sequences contain course work in Electric and Magnetic Fields, Digital Control Systems, and Pulse Power Systems. Required broadening courses cover the areas of Mathematics, Directed Energy Weapons, Rocket Turbines, and Technical Writing.

THE CURRICULUM

The primary sequence includes five courses dedicated to pulse power systems. Four of these are fundamentally oriented, and include topics like electromechanical energy conversion principles, modeling of electromechanical systems, power electronics circuits and devices, high power switches, pulse forming networks, modulators, lightning, EMP, and pulse transformers. For the most part, the combination of topics included in these four courses is unique to the AFIT pulse power program. The four courses are taught during three academic quarters.

The fifth course in the pulse power sequence is taught during the sixth quarter of the program, and immediately follows the full-time thesis quarter. This course is a very unique design course during which the class participates in an extensive group design project. At the beginning of the academic quarter, the class is assigned a very loosely defined task to design a complete pulse power system. They are given a "window" bounded by power level, system weight, and system volume. The goal is to produce a written specification suitable to be the work statement in a bid advertisement. The class must perform the necessary feasibility studies, sub-system tradeoff studies, and determine that the components will be compatible. The specification must include the control system, and electric and magnetic compatibility requirements. Faculty guidance during this design course is kept to a minimum; therefore, the students must unite as a design team to manage their own project. The course requirements are satisfied by the submission of an acceptable specifications package. The benefits derived from this course include the usual design experience, but most significant is the great increase in student confidence levels.

The sequence of courses in digital control includes topics such as the fundamental characteristics and design of linear feedback control systems, discrete-data systems which include digital computers; and, a comprehensive analysis of the theoretical and structural relationships between control theory, digital signal processing and digital system design. Extensive use of computer-aided-design is made throughout the sequence. The sequence of three courses is taught in a three academic quarter period. A design project is begun in the second course, and finally implemented as computer hardware and software in the third course. Much emphasis is placed on the impact of the very fast pulse power systems on the sample-rate limited digital controllers.

The electric and magnetic fields sequence contains two required courses taught during two successive academic quarters. Topics included in these courses are the general electrostatic and magnetostatic solutions to Maxwell's equations, dielectric and ferromagnetic materials, wave phenomena, and examples for specific geometries. In all areas, the general formulations are emphasized.

Two of the broadening courses are of particular interest. The first includes material required to understand and specify fast start turbine systems. It includes characteristics and performance of monopropellant and bipropellant combustion systems, and fundmentals of impulse type fast-start turbines. This is a two quarter hour course taught by the Mechanical Engineering faculty. The second course, taught by the Engineering Physics Department, addresses the philosophical and terminology gap that exists between practicing engineers and physicists when the topic is directed energy weapons. The course concentrates on the physics of target damage and provides the power engineer with useful tools for predicting the nature and magnitude of the power supplies required. This latter course is also taught in two quarter hours.

An important part of the Pulse Power Systems curriculum is the twelve quarter hour thesis effort that is distributed over the last three academic quarters. The first quarter's effort is for two quarter hours credit and is done in conjunction with a two quarter hour technical communications seminar. During this first quarter the student selects his topic, does the background reading, plans his efforts, and produces a very detailed prospectus of his thesis effort. This prospectus serves as the final written and oral requirement for the technical communications seminar.

During the second quarter, which is the fifth quarter of the program, the students devote full time to their thesis research. Most of this work is done in Department of Defense laboratories at many geographical locations. The students spend ten to twelve weeks on temporary duty at the laboratory, with all expenses paid by the laboratory. A unique feature of these thesis projects is their being a part of a larger on-going effort at the laboratory. The students, of course, gain tremendously from working intimately with experienced R&D personnel.

Thesis sponsorship has been provided by the Air Force Weapons Laboratory, Army Mobility Equipment Research and Development Command, Defense Nuclear Agency, Army Electronics Technology and Devices Laboratory, Aero Propulsion Laboratory, and Flight Dynamics Laboratory.

Thesis projects to date have included: Effects of a Pulse-Forming Network Operating Into A Nonlinear Load, Design Considerations and Optimization of a 0.1 μsec Risetime Lightning Simulation System, A Study of Rotor Geometries and Harmonic Performance of Synchronous Generators, Prime Power to Pulse Condition ing Interface Methods, and An Algorithm Generator for Performing Feasibility Studies of Pulse Power Systems.

Writing and defense of the thesis is done during the third quarter. During the same quarter the students are taking the design course. This permits the students to immediately apply the results of their thesis research to a major design effort.

SUPPORTING ACTIVITIES

The Pulse Power Systems Curriculum has been supplemented by a bi-weekly lecture series. This series of lectures covers a wide range of pulse power topics, including fundamental as well as advanced concepts. The lecturers are from industry, universities, and national laboratories. The lecture series is available to the entire Air Force Research and Development community. Lectures to date have addressed all types of prime power sources, pulse forming networks, and switches. The next major area to be addressed is power conditioning.

Students in the Pulse Power Program also benefit from the very close proximity of AFIT to many of the Air Force R&D laboratories. The Air Force Wright Aeronautical Laboratories are also located at Wright-Patterson AFB. Within this group, the Aero Propulsion Laboratory and the Flight Dynamics Laboratory are very involved with the development of pulse power systems. These laboratories have been very generous in making their personnel and facilities available to support the Pulse Power Program.

A number of engineers and scientists from the U.S. Army and the Department of Energy have given design seminars for the students during their design course. These seminars have proved very useful by exposing the students to differing design philosophies and requirements. Seminars such as these are extremely important to the technical education of the students.

SUMMARY

In response to Air Force requirements for engineers to develop pulse power systems, the Air Force Institute of Technology developed a special graduate curriculum within the Department of Electrical Engineering. These engineers are required to have a rather broad background in electrical engineering with additional specialization in energy conversion and storage, high energy switching, high energy electric and magnetic fields, and digital control systems. These education requirements are met by a six quarter curriculum that contains three basic course sequences, requires a thesis, and includes a number of broadening courses. The specific sequences are pulse power systems, digital control, and fields and waves. A system design course is included within the pulse power sequence.

The required thesis is distributed over three academic quarters with the middle of the three devoted to full time thesis research. Research for many of the pulse power systems theses has been performed in Department of Defense laboratories.

The first group of pulse power systems students graduated with Masters degrees in December 1980 and were all assigned to Air Force research and development activities. Reports from the new employers indicate that the graduates are very well prepared to move into their new assignments, and that they are very quickly assuming responsibility for advanced system development.