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Teaching Power Electronics to Electrical Engineering Undergraduates in an Interactive Two-semester Integrated Sequence

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Abstract

Power electronics instruction is presented in the context of an innovative, proven five-course undergraduate curriculum in electric power engineering. For the power electronics portion, there are five goals accomplished in two semesters within this framework. Courses have a 45-lesson semester format and use instructional methods shown to be successful for nearly twenty years. The program of instruction includes a laboratory program that uses appropriate laboratory equipment, kits, and a hands-on project to design, build, fabricate, populate, test, and iterate a DC/DC converter. Assessment summarizes nearly twenty years of successful instruction.

Introduction

Almost all electrical power in industrialized societies now is processed through at least one power electronic stage. As such, electrical engineers (EE) often encounter power electronic circuitry and systems when performing their routine duties. A knowledge of how these systems work gives an EE an advantage in understanding and working with power of a nature that is provided to every electrical system. As part of an innovative sequence of courses at the University of Idaho, electrical engineering undergraduates learn these power electronic systems in a hands-on, creative environment. The sequence was reported in an ASEE paper in 2004 [1]. It has been taught within the same framework since. This paper presents the power electronics track within this sequence of courses after an innovative project was added. The goals of the power electronics track are stated in the cover letter to the syllabi. They are

- Gain a propensity to use first principles to solve problems. We take a physical approach and use our circuit theory and electromechanical energy conversion fundamentals. A solid foundation in these will serve us well here.
- Improve our communications and problem solving skills. This means a great deal of oral presentation practice in the classroom and a written lab report.
- Understand methods and devices that condition electrical energy for our use. Introduce the analysis and design of power electronic circuits.
- Gain the ability to develop and apply mathematical models to predict behavior of electromechanical energy conversion from first principles.
- Gain a practical understanding of power electronics by designing, simulating, building, and testing practical power electronic circuits.

Curriculum and Context

The curriculum in which we teach power electronics consists of a five-course sequence in electrical power designed to serve a range of undergraduate Electrical Engineering (EE) students.

It has been taught in this same general format, subjects, and philosophy since its launch in Spring semester of 2003.

Each course is three semester credit hours, 45 lessons of 50 minutes each, three lessons per week on campus. All lessons in each of the five courses are recorded in a studio/classroom and distributed to off-campus students also. The first course in the sequence is a junior-level course that serves all EE students with electric power subjects that all EEs will likely encounter in their careers. These include AC single phase power, single phase two-winding transformers with underlying magnetics, electromechanical analogs, DC motors, DC/DC converters, billing for utility services, and household wiring. The second course is designed for EEs who will have responsibilities as engineers for the electric utility's customers. Its subjects include three phase AC power, three phase transformers, synchronous generators, and induction motors. The third and fourth courses serve EEs who plan to enter the electric power industry. The third course is a steady state treatment of the public electric utility power system, addressed by: review of three phase power, three phase transformers, power transmission lines, synchronous generators in context, load characterization, power system steady state models and simulation, power flow, and an introduction to protection and relaying. The fourth course addresses power system dynamics, modeling with dynamic models by the same component by component structure as the third course. Then we study system models and interactions, ending with transient system analysis and dynamics that influence protection and relaying.

Our fifth course in our undergraduate electric power engineering sequence is a senior-level technical elective in power electronics. It is the subject of the lion's share of this paper. The second through fourth courses strongly emphasize electric power systems. Of enrollments from 20 to 60 students in the first course, about 60% take the second through fourth course. Most of the students who take the second course stay for the third and fourth courses. This fifth course is an elective focusing more on electronics and less on power systems. The enrollment is not as large and the faces are not always the same as the other four courses in our sequence. About 40% of a class from year to year enrolls in power electronics. In our curriculum, we still treat this as an electric power course that contains electronics, not strictly an electronics course with a power emphasis as other universities such as MIT do. Nonetheless, we pick up a few electronics students and we lose several power students. While enrollment as a percentage of a given class group is nearly the same from year to year, the numbers vary widely because our class size likewise varies widely. For example, in 2017, 25 of a class of nearly 60 students took power electronics. In 2020, only two students registered, and the course was canceled. Registration was before COVID arrived. But in 2021, we returned near to the historical 40% level, even during COVID: 13 of a class of 30 took the course.

Teaching DC/DC Converters in the First Electric Power Engineering Course

DC/DC converters are introduced in the latter part of the first course in our sequence. Most electrical engineers will encounter power supplies at some point in their careers. This part of the course is designed to give some understanding of the issues underlying DC/DC conversion, how electronics engineers are provided with what they call V_{DD}, the DC biasing voltage that underlies electronic circuitry, whether analog, mixed-signal, or digital.

The subjects presented in about ten lessons are the buck converter, boost converter, and flyback converter. Steady state circuit analysis is the tool used in these lessons. Power electronics is presented as the control of a periodic sequence of circuit transients to understand and quantify voltage gain and energy efficiency in conversion of electric power to desirable voltage and power levels. Understanding the switching sequence of a buck converter and its energy storage behavior is first presented, followed by deriving the voltage gain of a buck converter. Using state variables, inductor current and capacitor voltage, the circuit's performance becomes apparent. These serve as a basis for strong insight into how power converters work.

When students understand these concepts, we then teach them to design a buck converter. Examples and homework reinforce this supporting approach. We follow by teaching the boost converter in the same manner and sequence. Important nonideal behaviors, such as semiconductor forward voltage drops, inductor resistance, and equivalent series resistance in capacitors, appear prominently for the boost converter. The homework then requires the student to do the same analysis and design for the buck-boost converter without classroom instruction addressing it.

When we introduce the flyback converter, the students' work on the buck-boost converter pays off. We can pay attention to the transformer as the new item in the circuit. There is less needed to understand circuit dynamics when they have already learned the buck-boost converter independently. With the flyback converter, we have found that analyzing energy flow and storage is the quickest way to understanding. If we have time, we reinforce this by introducing the single switch forward converter.

Laboratory work is an important part of instruction on these power converters. Laboratory work is presented later in this paper, amplifying an earlier ASEE paper on the topic [2].

A Power Electronics Course as a Senior-level Technical Elective in Our Sequence

Our fifth course in our undergraduate electric power engineering sequence is a senior-level technical elective. Its organization is fourfold:

- review of electronics and electrical power circuit analysis,
- DC/DC converters including both those without transformers and those with transformers,
- AC/DC converters, rectifiers, single and three phase, up to unity power factor converters,
- DC/AC converters, inverters, including Pulse Width Modulation of the standard topology and newer topologies such as Modular Multilevel Converters and Matrix Converters of several sorts.

Within each of the three converter categories listed above, we teach the circuits and their modeling first. We follow with a treatment of modeling and analysis of semiconductor devices prominent in each converter category: DC/DC (MOSFETs), AC/DC (diodes and thyristors), and

DC/AC (IGBTs). Each section ends with one or two lessons on important applications of the converter category at hand: DC/DC (build a converter), AC/DC (HVDC systems), and DC/AC (motor drives). This forms a nice symmetrical structure to the course.

For our power electronics course, its prerequisites are a two-semester circuits sequence and the first course in our electric power engineering sequence. Its corequisites are the second course in the electric power engineering sequence and the first, junior-level, electronics course. This power electronics portion of the course uses circuit theory intensively. More than half of the attention given to each topic addresses circuit methods of power electronics analysis.

Circuit simulation is done primarily in LT-SPICE, the simulation software that students use in their first electronics course. This year, we began to use ADS[9] for our simulations as a pilot program. Some simulation work uses MATLAB and Simulink, particularly the time domain circuit dynamics and frequency domain signal analysis for which these software simulators are well-suited. We encourage the use of MathCAD as the optimum vehicle for most of the analysis examples in class and to perform the homework. Students submit homework in pdf format; We use Gradescope to grade homework and exams[10].

There are two homework sets appropriate for about ten days of work each for the rectifiers and the inverters sections of the course. One homework set covers review topics and one homework set provides a foundation for DC/DC converter design. The latter homework set has four analysis problems addressing buck, boost, buck-boost, and flyback converters. It also has four brief design problems addressing buck, boost, flyback, and single-switch forward converters. These design problems are selected to provide a foundation necessary to propose, simulate, build, and test a DC/DC converter.

The text materials are from several sources, including two textbooks: Power Electronics, First Edition, by Daniel W. Hart [3] and Power Electronics: Circuits, Devices, and Applications, Fourth Edition by Muhammad Rashid[4]. Professor Hart's book is a 2010 update of his successful 1997 textbook with a different publisher [5]. He presents circuits and controls for a wide range of power electronic converters. It is our opinion, based on more than twenty years of use and trying several other textbooks, that Professor Hart's book is the best book for learning the fundamentals of power electronic circuits. Students seem to perform better when they learn from him. Unfortunately, Professor Hart is strong on his intended subjects of circuits and controls, but he presents little about semiconductor devices and power electronic applications. Therefore, we use Professor Rashid's book as our main textbook. He is strong in power semiconductor analysis, having devoted his career to that field. His explanations and models of the semiconductor devices that we teach are nicely appropriate for the level that we present them. He also has some excellent discussions of HVDC systems, motor drives, and power supplies. These fit nicely into the format and philosophy of our power electronics courses. Back when his second edition was the current one, we adopted his organization in our approach. We still use it: Circuits first followed by pertinent semiconductor devices and concluding with applications.

There is one power electronics exam in our first course, offered late in the course, covering DC/DC converter circuits. There are two exams in our power electronics course. The midterm covers the review of fundamentals of circuits, power, and electronics but its main thing is rectifiers. The final exam is comprehensive but it has an emphasis on inverters. The project to design, build, and test a DC/DC converter provides plenty of learning and testing in a highly interactive fashion. Each student receives an oral exam when presenting the final project report. There is little further need for more exams on DC/DC converters, though students each year request such an additional exam on their formal summative course evaluations.

Laboratory Component

In the first course, there is a single-credit laboratory component for which students register separately. The laboratory reinforces the major topics of the course: Two measurement labs, two transformer labs, two DC machine labs, two power electronics labs, and one household wiring lab.

The first of our two power electronics labs is a hands-on lab to wire up a lab demonstrator as a buck converter and then as a boost converter. Eric Cegnar created the lab equipment in 2004 when he worked as a design engineer for Digilent, a nearby manufacturer of instructional lab equipment. The lab equipment has Pulse Width Modulation generated by a microcontroller that Eric Cegnar programmed. Students wire up the power converter from a schematic. They then measure voltage and current waveforms in continuous and in discontinuous conduction and verify voltage gain for each converter in turn. See Figure 1. Therein, a Boost Converter is wired together in the center of the unit. The input power source and instrumentation are on the bench to the left. On the right is the circuit's inductor and load resistance. The controller is on the two smaller boards to the front of the Boost Converter.

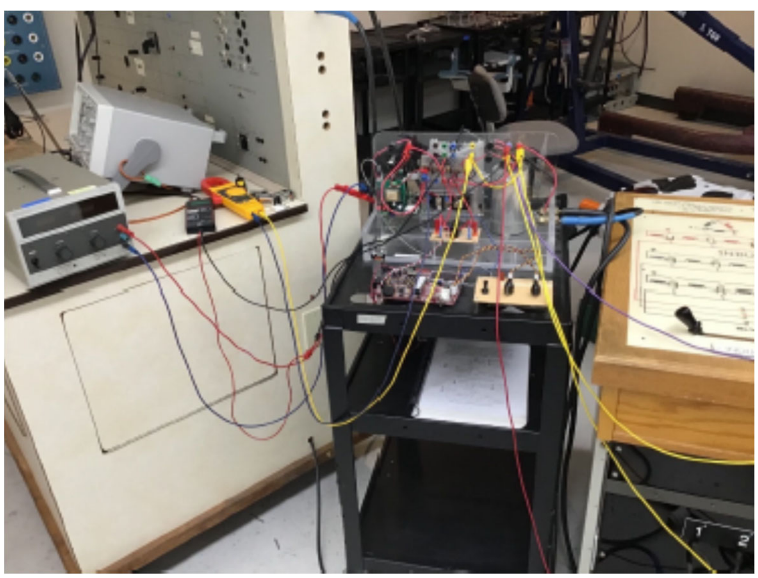

Figure 1. Power Electronics Laboratory Equipment

This is similar to other laboratory setups and procedures that a number of other instructional laboratory equipment companies provide. Our equipment is showing its age after nearly twenty years in service. This year, we began a fundraising effort as a top priority of our Dean to replace it and several other items within our electric power lab.

The second lab is to build and test a Minty Boost power converter. The Minty Boost is a kit that Limor Fried, principal at Adafruit, Inc., designed and sells to schools and hobbyists [6]. It is at heart a boost converter that uses two AA batteries to power a cell phone through a USB port. Students build this kit and add a loop of wire in series with the boost converter's inductor. They then measure inductor current on an oscilloscope using a clamp probe on the wire loop. They also measure voltage in put and output. They check the Minty Boost's voltage regulation by substituting a variable voltage power supply for the AA cells and reducing the input voltage until the regulation fails. This reinforces the idea that the Minty Boost has some immunity to battery voltage decrease with discharge. We get a volume discount when purchasing Minty Boost kits. Funding for the first decade came from an alumni gift but we now pay for them from student lab fees. Due to the nature of the hardware and its usefulness outside the classroom, alumni often show off their Minty Boost charger when they return to campus for a visit several years later. More alumni have shown me more Minty Boost chargers still in use than all other lab work and undergraduate project results combined.

Project to Teach DC/DC Converters

Though the power electronics course has no formal laboratory curriculum, it is by far our most laboratory intensive senior-level course in electrical engineering. The reason is the course project. Students are required to design, build, and test a DC/DC converter to a given set of specifications. They must design a transformer-based converter, such as a flyback converter or a forward converter, or they must design two DC/DC converters without a transformer, such as buck converter and a boost converter. The design follows directly from procedures learned from their second homework set. Because they already had ten lessons in DC/DC converters with their previous course, we only have a brief review, some instruction on MOSFETs, and a homework set that is mostly review in nature.

Simulating the converter follows the design. Most students use a SPICE-based simulation because that is taught in their electronics course. They order parts based on what they found from their designs and simulations. While they are simulating, a series of four lessons teaches them performance and selection of a range of electronic components: resistors, capacitors, inductors, MOSFETs, diodes, oscillator or PWM chips, and MOSFET drivers. During this time, they learn circuit board design and layout so their components can be selected with a chance of being practical. While selecting components, they receive a lesson on creating circuit boards with Eagle or KiCAD. We have our own circuit board router purchased from LPKF Laser and Electronics AG[8] in nearby Portland, Oregon, and funded by a gift from an alumnus in 2018. The result is a consolidated parts order and Gerber files sent to our technician before they leave on Spring Break. When they return, their components have arrived and their boards are ready for populating.

Their first try is rarely successful. Most of the students have never built a project on a circuit board before taking this class. As a professor, I catch the most obvious mistakes before board fabrication but there is a great deal of learning accomplished by allowing students to find out that their board fails testing for some elementary reasons. Herein lies the strength of this project: They must go back to their design, revise their boards accordingly, and submit another Gerber file and another consolidated parts order. The second board is built and tested in early April. After the second round of testing, students must present their board in person to the professor. They must show that it meets specifications, exercising an important oral communication skill. Each year since we started this project, about 40% of the boards work when presented to the professor. The professor brings another 20% to 40% to meet specifications by providing individual instruction during the demonstrations. Therefore, from 60% to 80% of the students have a working board by the end of the project. Some student boards are shown in Figures 2 through 5.

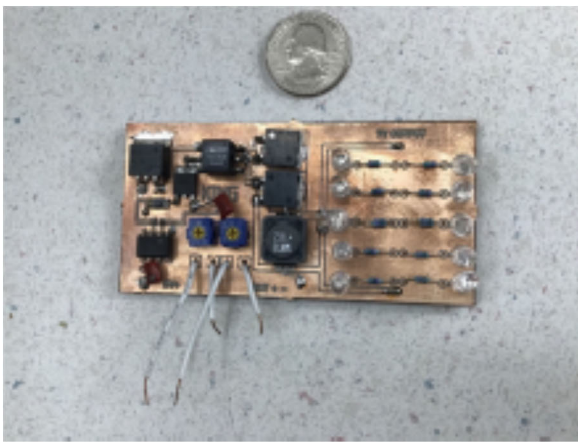

Figure 2. Boost Converter with Signal Generation and Automated Load

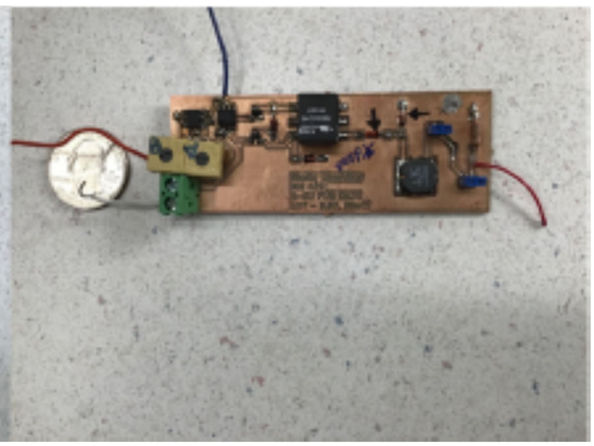

Figure 3. Two Switch Forward Converter Designed and Built by Student

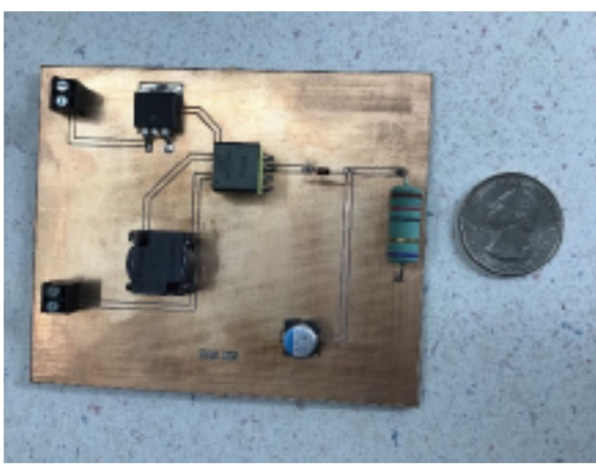

Figure 4. Buck Converter, Not Optimized For Space Utilization, Student Work

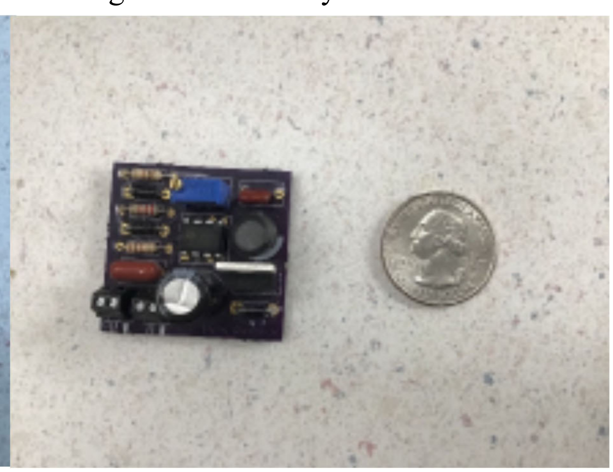

Figure 5. Buck Converter with Signal Generation and Load, Optimized for Space, Student Work

We pay for the project with gift funds. One of our alumni was in the first cohort of students who did this DC/DC converter design project back in 2014. That year, the professor funded it with his own money because it was considered a risky idea. When that student graduated, he credited his experience with this project and his experience as an undergraduate research assistant in power electronics as being highly important to his landing his first and second jobs in industry. He has funded the project with a designated gift to the university each year since.

Assessment

We assess this course based on a few indicators. These include enrollment numbers, success rates on meeting project specifications, and anecdotal evidence from job interviews.

First, we track enrollment from year to year. The power electronics course fits into a six-course technical elective requirement for graduation. It does not fit into any mandatory or planned curriculum track. Our students talk to each other. They know what courses are worthwhile and which should be avoided. Therefore, enrollment in this power electronics course is a good indicator of their perceived effectiveness of the course. Enrollment from year to year is typically about 40% of the electrical engineering majors in the class at hand. Variations have not been large enough to be statistically significant with one exception. When the professor went on sabbatical in 2020, the students knew before registration opened that the course would be offered but the project would not be in it. Instead of being 40% of a class of 35 students, enrollment dropped to only two students. The course was then cancelled for that year. The following year, enrollment was 15 students from a class of 30 students.

Second, we track success rates in meeting specifications for the project. Only one student in six years has met specifications on the first try. However, success has been consistently about 40% on the second board. Students rarely meet specifications on the first board. Few students have even created a board before this. Their learning about power electronics well enough to have a working board on the second try is promising. We have found that another 20% to 40% will have boards that meet specifications after the professor makes some adjustments during the demonstration phase. This sums to a 60% to 80% success on the project requirements, a reasonably successful result.

Another proof of success comes later within the curriculum. Students sometimes build PC boards for their senior projects. The PC boards built by students who had this experience in their power electronics course usually perform close to specifications of their senior project on the first try. Their final oral presentations are routinely superior to students who did not take this power electronics course. The same professor teaches power electronics and senior design, so this correlation is easier to observe.

When students go on job interviews, we recommend that they include their boards in the topics addressed in the interview if they feel it may help them. They return telling, in most cases, of how the interview changed tone dramatically when the interviewer heard that the student had built a power converter on board and it performed to specifications. Interview after interview produced the same feedback. Apparently, there is a need for young engineers who can build a circuit board to specifications. This is an indicator that the course is meeting a need of a critical constituency.

As mentioned earlier in this paper, the Minty Boost battery charger has anecdotally returned to campus years later in the pockets of more alumni than the results of all other undergraduate projects combined.

Conclusions

The University of Idaho organized an electric power engineering undergraduate program and has taught it continuously since 2003. Its five courses provide an escalating introduction, designed for students in levels of involvement in the industry as electrical engineers, whether those with only cursory contact with power, as engineers working as the industry's customers, or as electric power engineers pursuing a career within the utility industry. Within this curriculum, power electronics is taught in ten lessons on DC/DC Converters in the first course in the sequence plus the entirety of the fifth and final course. Instruction is organized into four topic areas: AC circuits and power, DC/DC Converters, AC/DC converters commonly called rectifiers, and DC/AC Converters that perform as inverters. Within the three power converter topic areas, instruction follows the model of learning a circuit approach first, followed by lessons on important power semiconductor devices, and concluded by a lesson each on important applications. The courses have a significant laboratory component, whether taking measurements on laboratory benches that are mostly prewired, building and testing a Minty Boost kit, or doing a complete design, simulate, build, populate, test, and design iteration. In-house software and even a PC board router, provided as an alumni gift, make for an experience that student find to provide them an advantage in their first round of job interviews and on their first career positions.

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