Power Electronic Converter for Double Duty in Design and Analysis Courses

Herbert L. Hess
Department of Electrical and Computer Engineering
University of Idaho, Moscow, Idaho

Abstract

A power electronics project offers a productive and inspiring environment for a capstone design project. Students design and build five different power electronic converters. These converters must perform as specified, have readily identifiable topology and components, and be reliable and easy to use. Design process and the development of circuit topologies, prototype boards, and software are presented. When completed, the converters go to work as demonstrations in a senior-level course in power electronics. Converters show fundamental circuit behavior on ordinary portable laboratory instruments. Common nonideal behavior of converters appears and can be used to gain better insight into circuit operation than that often gained by traditional simulation methods. These converters also were used as a recruiting tool. Methods of teaching with these converters are presented, including some that worked and some that failed.

Introduction

Power electronics draws from a host of topics, making it an appropriate vehicle for teaching design to senior undergraduate students. One of the purposes of such design courses is to require the student to bring skills and knowledge, learned from a variety of courses and experiences, to bear on an open-ended problem. In power electronics, open-ended problems abound within the capabilities of students having a fairly broad electrical engineering undergraduate education. These problems draw on knowledge from a wide range of knowledge in electrical topics. These topics include device electronics, power and energy, signal processing and control (both analog and digital), electromagnetics, thermal design, and several others.

In an introductory course in power electronics, students benefit greatly from seeing power converters in operation. Students benefit even more from an opportunity to experiment with those converters. There are only a few basic converter topologies for ac to dc power conversion and dc to dc power conversion. Therefore, a few circuits can demonstrate most of the introductory concepts. Unfortunately, most introductory courses in power electronics are often offered with little opportunity to see a power converter in operation. Computer simulation is usually the core of most laboratory work in power electronics, when offered. This approach fails to take advantage of a behavior excited by the fundamental curiosity that drew many students to engineering in the first place: dissection of hardware.

This paper addresses a way to obtain useful hardware for students to investigate. Building such hardware is a wonderful vehicle in which to engage senior capstone design students in a project that draws from a host of skills that they have learned. Power electronics is usually taught as a senior-level elective [1], so the senior-level capstone design students understand their customer exceptionally well. By its very nature, elementary power converter circuitry tends to be quite robust. Consequently, the hardware allows practical illustration of important concepts with a hands-on approach to learning.

In this paper, the design of these working power converters is first explained. Beginning with a simple Request for Proposal (RFP), the design students go through the design process. Second, this paper presents the results of their design work. These include schematics, photographs, and some notes on creative variations in their power converter designs. Third, this paper shows how the power converters are used in a power electronics course to teach power converter operation. Insights are gained from the experience of students who learned from this hardware. Some surprising applications for these circuits have appeared. Finally, the paper discusses some changes in teaching methods that this hardware encouraged.

EE480 Up-Down Converter
Project #2

An up-down converter, also know as a buck-boost converter, must be designed to the following specifications:

1. Voltage: Input voltage is 12Vdc. Output is variable over at least a range from 5 to 24Vdc. Ripple is 0.3V peak to peak.
2. Current: ripple is less than 20mA for all output voltages.
3. Power output is at least one watt.
4. Control: Output voltage must be manipulated by a keyboard and/or mouse commands from a PC.
5. Display: A graphical user interface is required. Output voltage must be displayed on the video display of a PC. Capability to display waveforms on an oscilloscope must be included.
6. Isolation: the PC must be galvanically isolated from the converter.
7. Temperature: No component may exceed 60°C.
8. Packaging: Easily transported without damage. Minimum of external cabling required for operation. Power components easily visible. Rugged enough to be moved repeatedly to a classroom.
9. Operators manual: complete instructions to assemble, start, and operate the system. Use of graphics is encouraged.

Figure 1. Request for Proposal

Request for Proposal

For the capstone design students, the project began with a brief Request for Proposal (RFP). They had just completed analyzing the effectiveness of a simple product, a power supply built from a kit. In their investigation, they were quite enthusiastic and thorough in identifying the good and bad points of the product. They encountered design tradeoffs. They asked, “How is this product the best possible value for the customer?” The next project for the course would require them to become the designer, creating a product of their own: a power converter.

The RFP was brief and simple. There were five different RFPs, each containing nine similar requests on a half sheet of paper. The RFP for the Up-Down Converter is shown in Figure 1. The other converters were a Buck Converter, Boost Converter, Phase-controlled Rectifier, and a Forward Converter. These designs are not of equal difficulty, so the students were carefully matched to the project and to each other. The senior capstone design instructor had already had each student in a mandatory junior-level course and was teaching several of them concurrently in the power electronics course.

Design Process

Fifteen students worked in three-student groups. Proposals were due in two weeks. Proposals answered the questions : "What?" and "How?" Proposals contained circuit schematics, but assigned no numerical values to components. Design reviews, three weeks later, contained components' numerical values and sufficient information to order parts and to build a prototype.

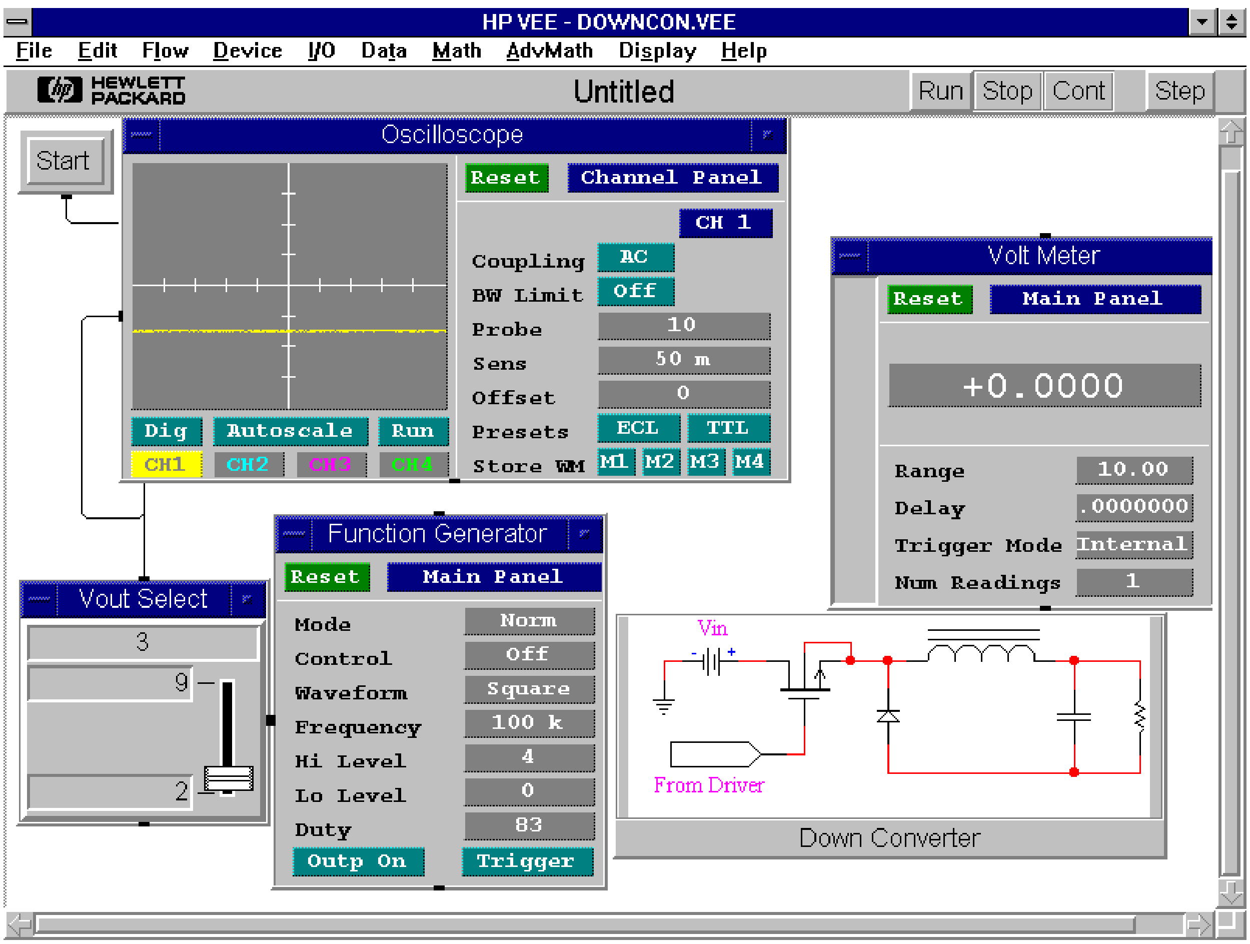

Figure 2. Display for Down Converter

Students tended to divide tasks as follows: one student designed and wrote the software for control and data collection, a second student designed and built the converter circuit, and a third student designed and built the display. The university had a copy of Hewlett-Packard Visual

Engineering Environment (HP-VEE) and HPIB Interface Boards, defining the third student's work rather well. This also placed the third student in a position to coordinate the project best. The students all developed this particular task organization on their own, without faculty direction.

Software design proceeded smoothly for most groups. The student designers quickly learned the necessary skills and built their displays. A sample display, in this case for the Buck, or Down, Converter is shown in Figure 2. Input controls are of two types: those for the converter and those for the instrumentation. The converter control is a "slider" to select the desired output voltage, required to be between 2V and 9V. Instrumentation includes a function generator for input of a switching signal and a voltmeter and an oscilloscope to read the output voltage and observe important waveforms, respectively. In this display panel, these students included a simplified circuit schematic for illustration, though not all groups included this.

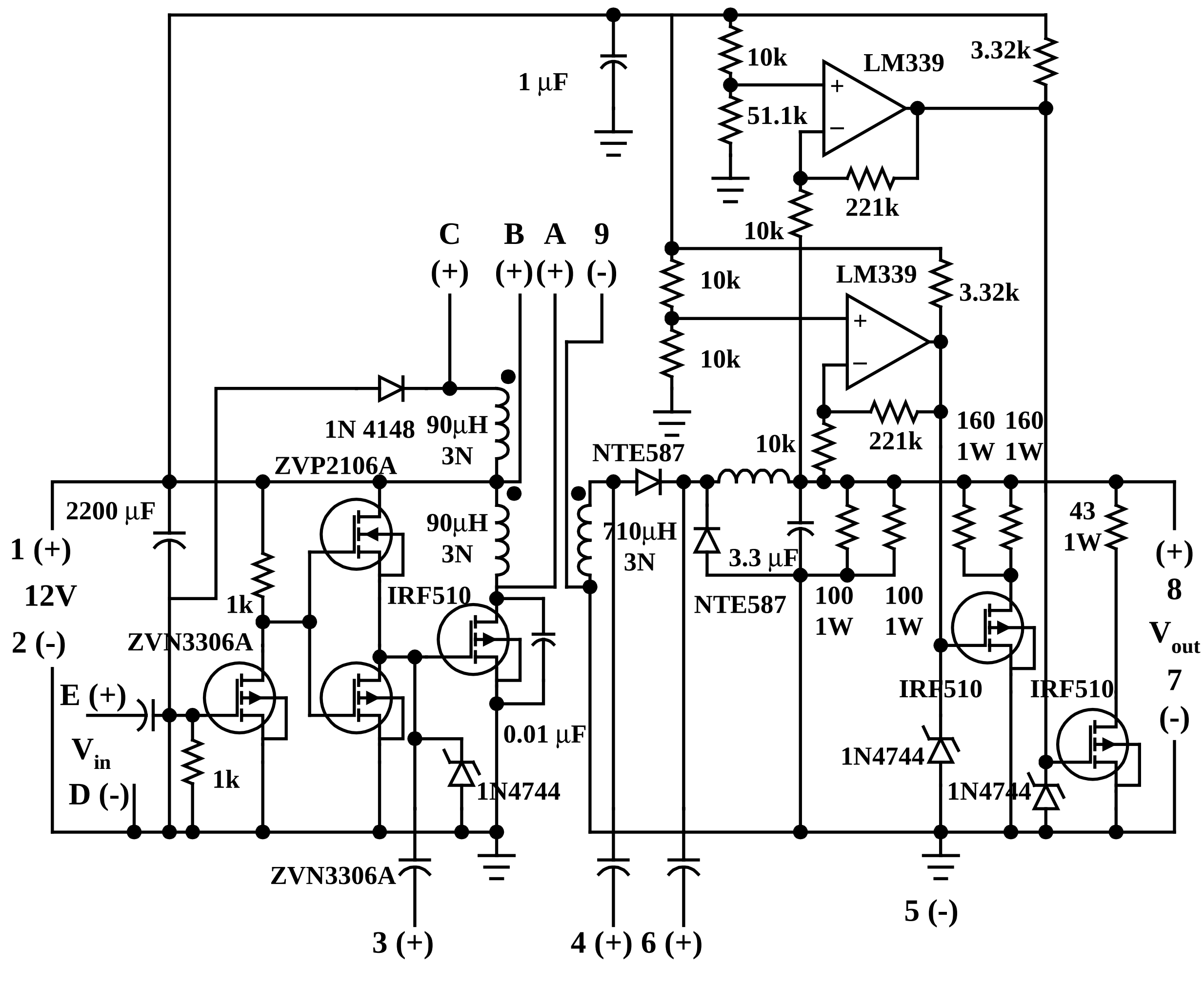

Figure 3. Circuit Schematic for the Forward Converter

Circuit Schematics

The students designed complete circuit schematics. The circuit schematic for their Forward Converter, for example, is shown in Figure 3. The designs all included three main functions for the circuitry: perform as expected, have easily identifiable topology and components, and be reliable and easy to use.

First, the circuit hardware must perform its fundamental operations. A Boost Converter must boost the dc voltage. A Rectifier must convert ac to dc. Output voltages and currents are governed by fairly simple relationships. Appropriate ideal waveforms appear in power electronics texts [2,3]. For brevity, they will not be included in this paper.

Most circuits did these tasks as expected. The Up-Down Converter group did fail to produce a working product because one group member quit the university during the final month of the year. The reasons were of a family nature, not related to the student's technical abilities. All other groups, however, produced robust, working converters.

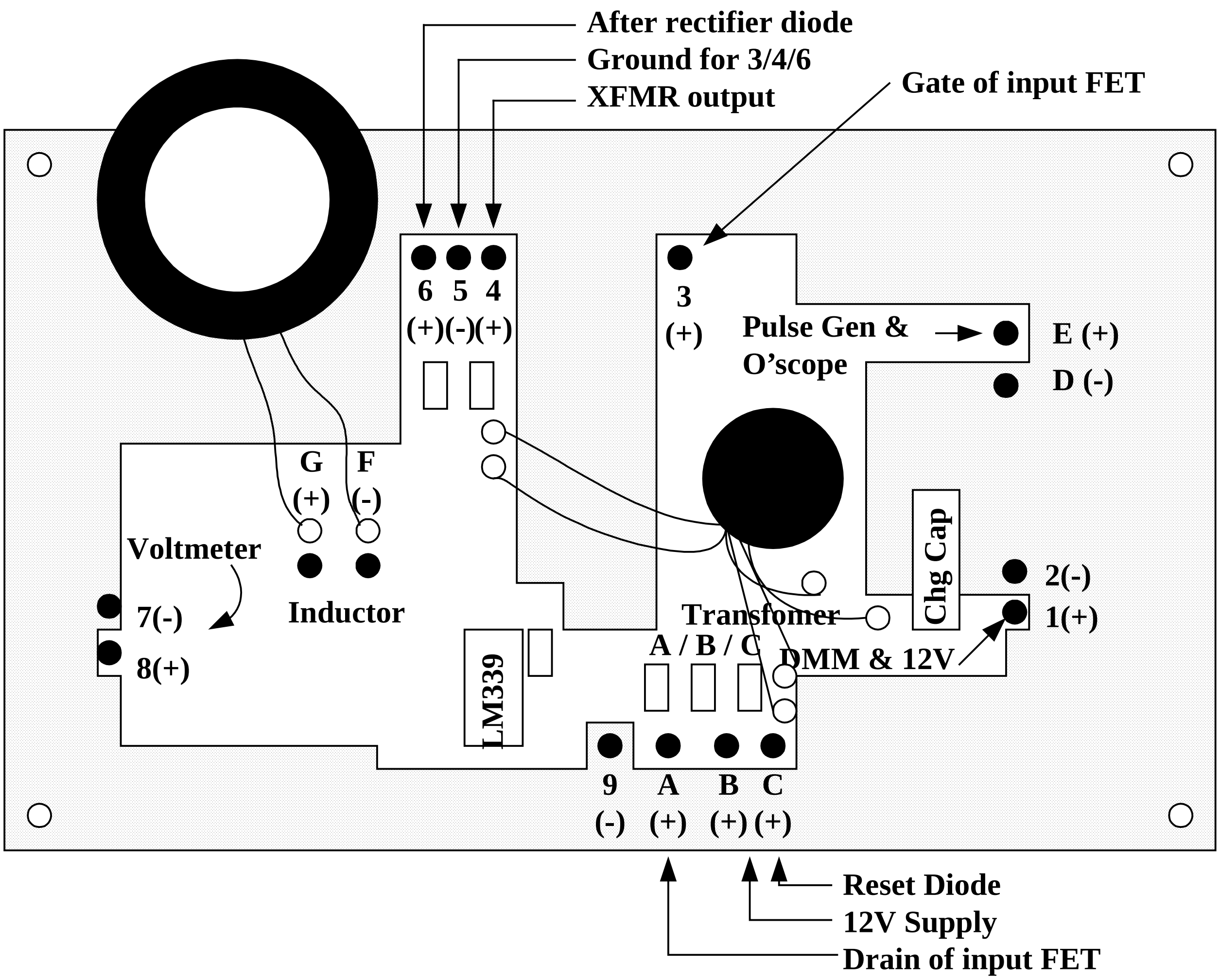

Figure 4a. Diagram of Forward Converter's Layout

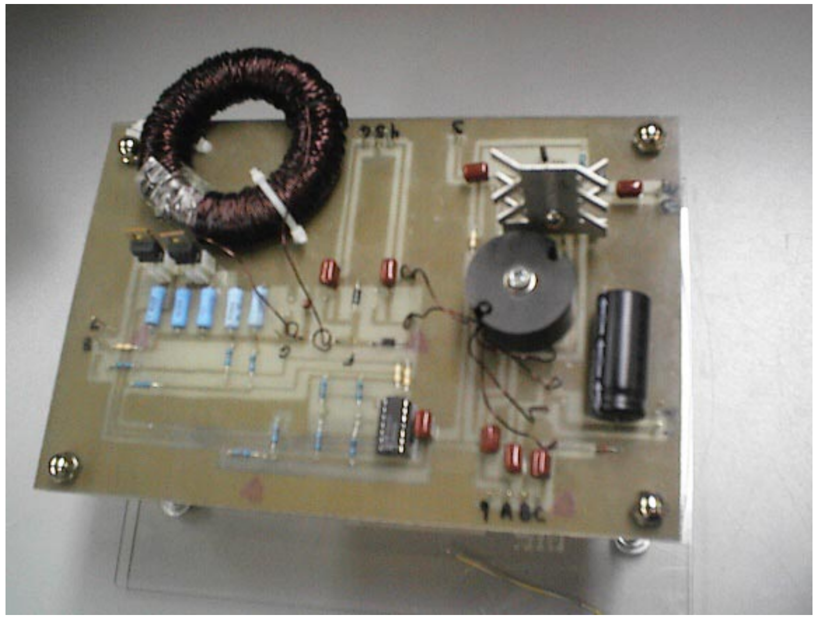

Figure 4bForward Converter Circuit Board

Nonideal behaviors are important in designing and in understanding these circuits. In fact, the lion’s share of development time in commercial design and production of power convertes is devoted to control of nonideal behaviors. An example is high-frequency ringing of the device’s terminal voltage at turn off due to underdamped oscillation between device capacitance and lead or trace inductance. The successful circuits also exhibited the common nonideal behaviors quite well. Substantial effort went into insuring that the desired behaviors would dominate. For example, the Forward Converter operates at 100 kHz, a capability that required three redesigns and fabrications of its layout to master its voltage ringing. The design is quite remarkable for a circuit with such a difficult combination of layout and operating frequency. A diagram and photograph of the layout of the forward converter board is shown in Figure 4a and 4b, respectively.

The second function of the circuit is displaying its components so their function is easily identifiable. This is where the students’ experience as students became most valuable. All circuits have topologies that are easily traceable. Each circuit is arranged so that the major components are easy to identify. An example is the forward converter shown in Figure 4b. Component placement supports an explanation of circuit function to the detriment of realistic and efficient populating of the circuit boards. Component placement also aggravated nonideal behaviors. For example, it caused most of the voltage ringing problems of the Forward Converter. The Boost Converter board, labeled to show that the major components are easily visible, is shown in Figure 5.

The third function of the circuit is to interface easily to the instrumentation. Explicit test points were labeled for easy identification. An example of this is shown in the forward converter diagram in Figure 4a. Connectors were explicitly designed to make instrument connections easy. As a result, an instructor can bring these circuits to class and, though making all connections quickly in front of the class, the instructor can expect reliable operation every time. None of these circuits has disappointed this instructor yet in five years of use.

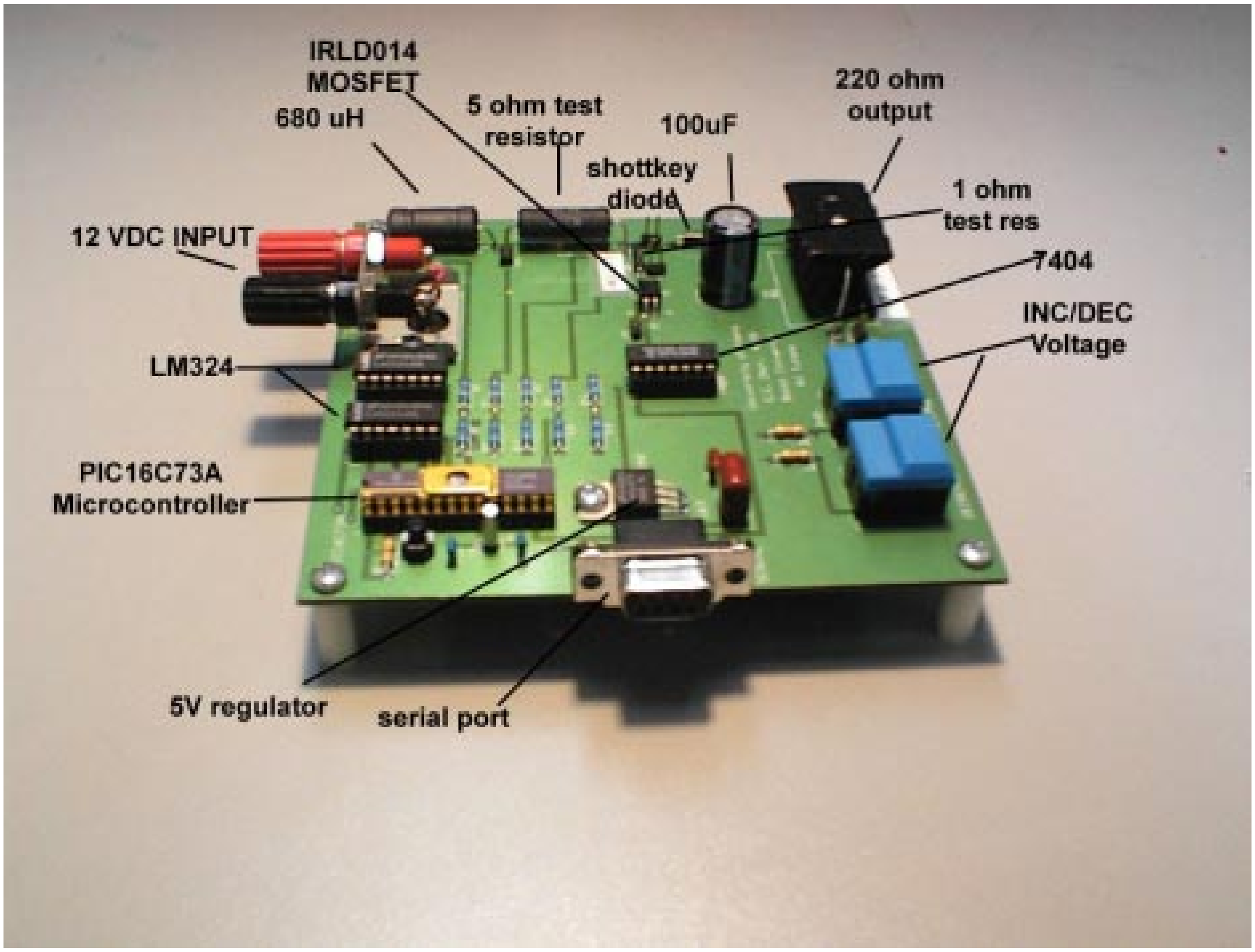

Figure 5. Boost Converter Circuit Board

Each project group wrote a users' manual for their converter. The requirement shown in Figure 1 was clarified: to provide a manual that would describe every step necessary to set up the converter for operation, concisely and completely. The manuals were an extra burden for the designers, but the manuals have dramatically extended the length of the project's useful life. A quick glance through the manual is all that is necessary to set up and operate any of the converters. The circuits are used in class just infrequently enough to make these instructions of great value.

Students added their own creative ways of showing circuit operation. The Up-Down Converter, as required in Figure 1, has an output voltage range from 5V to 24V. The minimum output power required is 1 Watt. If a single resistor is selected as a load, the 24V option produces nearly 20 Watts. Students designed an automatic load shedding circuit to reduce the component size and cost of their main converter. The circuit uses analog comparators to connect or disconnect load at appropriate output voltage levels. Though the Up-Down Converter group failed to build a converter, other groups seized the idea and made it work. For example, a similar load-shedding circuit appears in the Forward Converter: the five load resistors are in the lower right portion of the circuit schematic shown in Figure 3 and the control circuitry is above them.

For the Buck Converter, the student mounted a motor and fan on a pedestal to serve as a load. Modifying the airstream of the fan changes the load torque in a way that is easily understood. This obvious manifestation of the speed and torque proved to be a pedagogical gem. The Buck Converter and its motor load is shown in Figure 6.

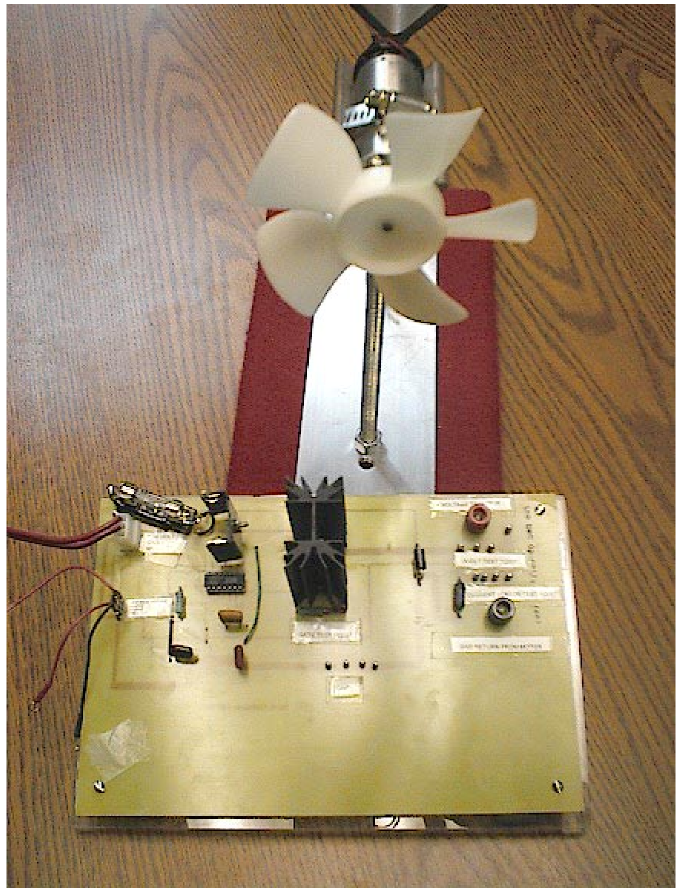

Figure 6. Buck Converter with Motor and Fan Load

Application

These converter circuits worked as well as expected in the senior power electronics course. They performed reliably each time that they were used, typically once or twice a semester.

At first, a tower of instruments accompanied the converters. This tower contained the computer, a four-channel oscilloscope, two voltmeters, a function generator (having a square wave option with a variable duty cycle capability), and voltage and current isolation for every measurement. This soon became cumbersome. It also tended to frighten the students. When left alone in the classroom and told to "feel free to play with the converter circuit," none seized that opportunity. Consequently, the tower was abandoned and portable instruments were acquired. Because the individual instruments were the same as found in the teaching labs, students were more apt to investigate the circuits when given the opportunity. Through experience, it was determined that showing a circuit at least twice, once for introducing the instruction and once for reviewing the instruction, was quite effective.

Abandoning the tower in favor of more easily portable instruments eliminated the automated instrumentation capability. A portable oscilloscope, a hand-held digital multimeter, and a small function generator could be easily set up in a classroom for these reliable circuits. However, it became evident that a PC did not add enough to justify the extra setup time and complexity for sections of five to fifteen students. The exception to the portable instruments occurred when using the converters as part of a video outreach class. In that class, the computer monitor was connected to a video camera. The image was transmitted live across the state on public television. Another video camera, placed overhead, brought the circuit board into full view of every student, magnifying the layout and topology quite effectively.

Using these circuits as a recruiting tool proved to be an unexpected bonus. Sophomore Seminar is a once-a-week course to introduce students to a wide range of topics within electrical engineering. With little notice one Friday morning when the speaker called in sick, the Buck Converter and its Motor-Fan load were asked to introduce “Why You Should Consider Electric Power Engineering.” This converter with instruments was set up in less than five minutes in a building across the street. It performed flawlessly. On the written course critique at the end of the course two months later, several students wrote the unsolicited comment that the motor demonstration was the most interesting and inspiring of the entire semester’s presentations. Interest in electric power courses and internships among those students is nearly fourfold greater than in any of the previous three years.

One of the students who built the rectifier investigated a digital phase locked loop method of synchronizing the trigger pulses. Though an undergraduate, his work became the subject of a journal paper published the following year.[4]

Experimental Teaching Method

This fall, discussions among several faculty about how students become interested in engineering prompted an experiment. As children, future engineers often become interested in engineering by the process of disassembling pieces of equipment to find out how the work. After considering this, an experiment to improve teaching was considered.

One of these converter circuits would be used to introduce a topic, in this case, Buck Converters. These circuits encouraged a slightly different approach to teaching power electronics. They are rugged and durable. Their customers designed them. They can be taken into class with a few portable instruments. After showing a few waveforms and watching the output voltage vary in response to the duty cycle, the instructor asks the question, “How does this work?” Hearing little response to such a broad question, he would “peel back the lid” and everyone would start looking. The instruments showed output voltage tracking the duty cycle. Deriving that relationship mathematically is quick and easy. More observations and questions led to an understanding of why the converter switches instead of operating linearly, how switching losses occur, how the switching device is triggered, how energy storage enables the converter, etc. The appropriate math and analysis was presented as each question arose. Most of the questions came from the students.

The method seemed to have merit. Assessment of this will be presented at the conference, after summative reviews of the course from two semesters have been received.

Summary

In this paper, the design of the converters is first explained. In a senior capstone design course, fifteen students designed and built them from a unified set of specifications. These students also build an automated instrumentation interface to control the converters, with real time display of waveforms and high level commands for open-loop control. Design students did this with a stake in the process—in several cases, they were also the customer. They were contributing in an obvious way to teaching the next group of students what they had just learned. Their insight in this manner greatly improved the product.

The result is a set of circuit boards with operating instructions for hands-on use by power electronics students. Circuit diagrams, photographs of circuit boards, layouts, and automated instrumentation commands and displays will be shown in the paper. Assessment results of effectiveness will also be presented at the conference.

References

[1] Hess, H. "Power Electronics Instruction: Topics, Curricula, and Trends." *International Journal of Engineering Education*, XV, 5, November 1998, pp. 256-263.

[2] N. Mohan, T. Undeland, and W. Robbins, Power Electronics, Second Edition (New York: Wiley, 1995), chapter 7.

[3] P. Krein, Elements of Power Electronics (New York: Oxford, 1998), chapter 4.

[4] Wall, R.W., and H. Hess. "Design and Microcontroller Implementation of a Three Phase SCR Power Converter." *Journal of Circuits, Systems, and Computers*, VI, 6, December 1996, pp. 619-633.

HERB HESS

Herb Hess received the PhD degree from the University of Wisconsin-Madison in 1993. He served on the faculty of the United States Military Academy from 1983-1988. In 1993, he joined the University of Idaho, where he is Associate Professor of Electrical Engineering. He received the Best Paper Overall Award for the 1999 ASEE Annual Conference. His interests are in power electronic converters and electric machine drive systems.