BYOE: A Flexible System for Visualizing Switching Regulator Operation

Dr. Harry Courtney Powell, University of Virginia

Harry Powell is a Professor of Electrical and Computer Engineering in the Charles L. Brown Department of Electrical and Computer Engineering at the University of Virginia. After receiving a Bachelor's Degree in Electrical Engineering in1978 he was an active research and design engineer, focusing on automation, embedded systems, remote control, and electronic/mechanical co-design techniques, holding 16 patents in these areas. Returning to academia, he earned a PhD in Electrical and Computer Engineering in 2011 at the University of Virginia. His current research interests include machine learning, embedded systems, electrical power systems, and engineering education.

Kay Hutchinson, University of Virginia

Kay Hutchinson is an Electrical Engineering Ph.D. student at the University of Virginia. She obtained her Bachelor's Degree in Electrical Engineering from the University of Virginia in 2018 and joined the Dependable Systems and Analytics lab led by Professor Homa Alemzadeh. Kay Hutchinson's current research interests include surgical robotics, autonomous systems, and cyber-physical systems.

BYOE: A Flexible System for Visualizing Switching Regulator Operation

Introduction

At the University of Virginia, we have experienced increased student interest in alternate and renewable energy topics in Electrical and Computer Engineering over the past five years. This has presented a challenge, as we currently only offer a single "Electromagnetic Energy Conversion" course, which is in a lecture format with a required associated laboratory section. To address this challenge, we have been systematically phasing out older topics, i.e., D.C. motors, and adding course content relevant to photovoltaics and wind energy production, i.e., microgrids [1]. This has necessitated a redesign of some of our laboratory experiences and required us to reconsider the most efficient way to transmit a breadth of understanding while allowing students to explore selected topics in greater detail.

A fundamental building block of all photovoltaic and wind-based energy systems is the switching voltage regulator. This device enables changing system D.C. voltage levels with exceptionally high efficiencies, in many cases comparable to transformers for A.C. systems. This basic building block also appears in D.C. to A.C. conversion techniques for grid-connected devices. As a first step in updating our laboratory sequence, we elected to include material and experiments related to switching regulator design.

In this paper, we present our device and give complete design information. We describe how it may be used in various classroom and laboratory settings and adapted to different levels of course material. Simulation information is also included and we show how the simulations may be compared with the experimental observations. All contents are open-source, and the authors will supply complete design packets.

Background

We have examined, and employed in past classes, commercially available switching regulator evaluation boards [2]. While they are quite functional, they provide limited opportunity to explore the various parameters that determine the overall design, and how controlling each parameter individually may affect the overall performance of the system [3]. Other commercial devices offer increased flexibility, but are expensive and require other support laboratory equipment to function [4].To address these limitations, this BYOE paper describes an experimental apparatus that we designed that includes the two most common building blocks: the buck regulator, and the boost regulator. It incorporates a popular embedded computing platform, the National Instruments myRIO™, which is available at a very modest cost [5]. The regulator control board is designed with a standard and readily available suite of components easily obtainable through distribution channels, and can be assembled for approximately $100. This design was first employed in our "Electromagnetic Energy Conversion" class in the Spring of 2019 and will be used in this course in Spring 2020 and beyond. Student comments in the first offering of the lab were very favorable, and most agreed that the experiment enhanced their understanding of the basic concepts beyond simulation exercises. They also commented that seeing the feedback systems in action was an aid in grasping that essential theoretical element of operation.

Description of switching regulator module

The regulator module, attached to a myRIO, is shown in Figure 1 below. Note the compact layout of the device and the simple construction. The only other requirements for a complete experiment are a source of D.C. voltage and a load resistor. This module contains both full buck and boost regulator modules, each of which is controlled by the myRIO.

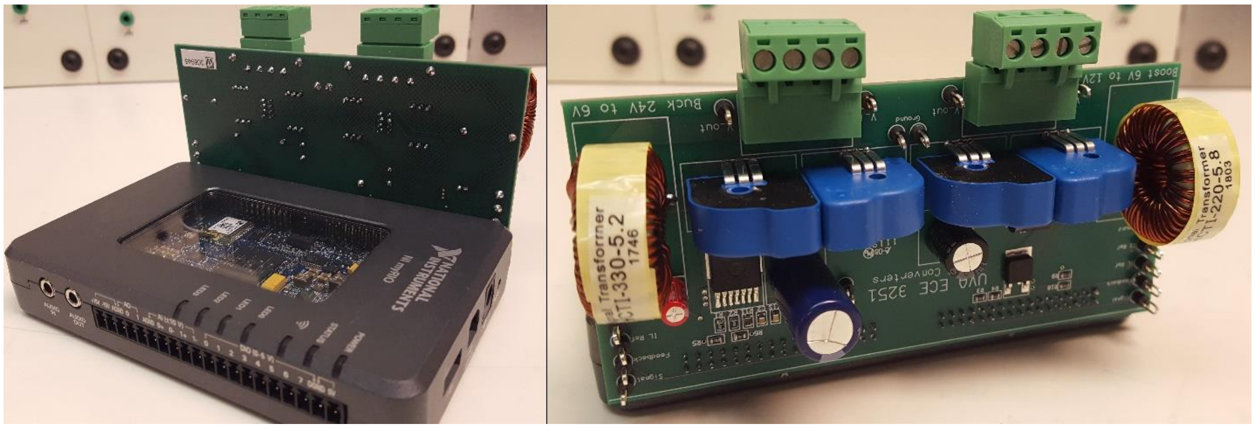

Figure 1 Assembled Switching Regulator Modules

A complete laboratory setup is shown in Figure 2 below. Note straightforward bench equipment requirements. Although a bench power supply is shown for the source of D.C. power, we have also successfully employed inexpensive photovoltaic panels of the type used for camping equipment and other outdoor activities. Resistors of sufficient power rating may be used as loads.

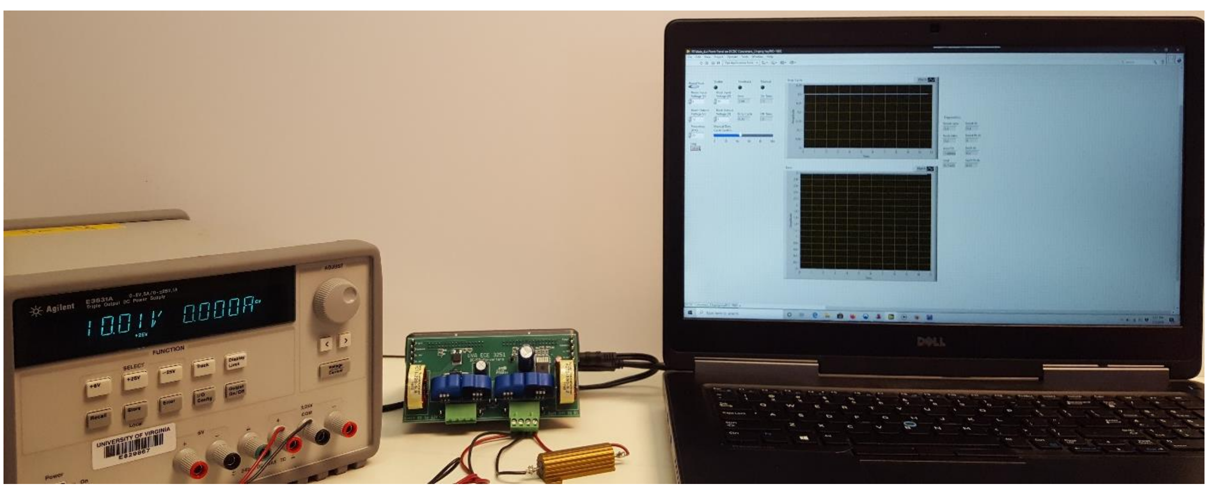

Figure 2 Complete Lab Bench Setup

There are two sets of connections to the regulator, in addition to the back plug-on connectors for the myRIO, one each for the buck and boost regulators, shown in Figure 3. These connections are detachable to allow for expedited switching of power sources, and both power sources and loads may be connected simultaneously, with the logic of which regulator is controlled handled by the logic of the myRIO controller. The uncontrolled regulator is off by default. The buck regulator accepts input voltages of 6 to 24 volts and controls the output to 3 volts at up to 5 amps. The boost regulator accepts 6 to 12 volts input and regulates to 12 volts out at 5 amps.

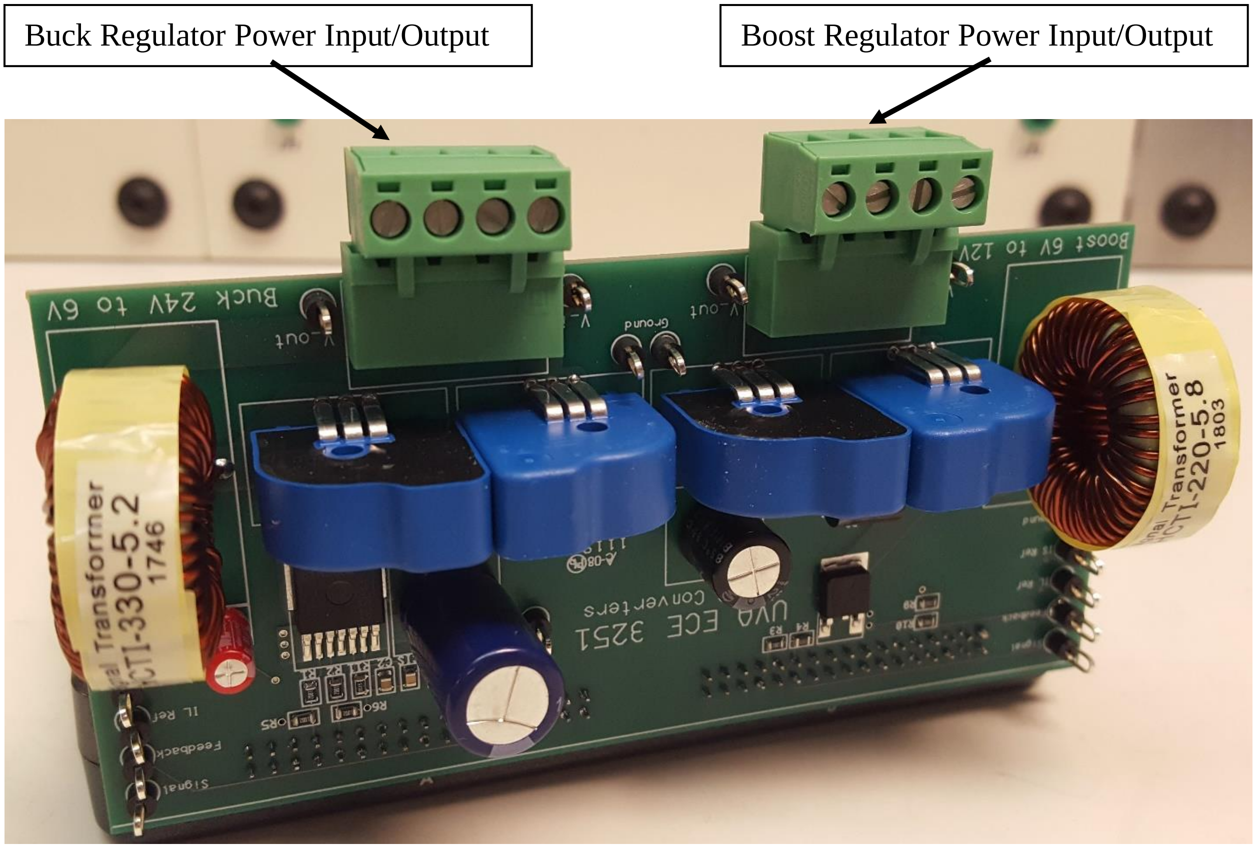

Figure 3 Power Input and Output Connections

Circuit Description

The boost and buck regulators share a joint circuit board and are both controlled by the same microcontroller, but otherwise are independent circuits. The buck regulator schematic is shown in Figure 4. Note that all connections not shown are from the myRIO I/O connector. There are several distinguishing features of the design. The switch element is a BTN8962 from Infineon [6]. This device operates with standard logic levels for all control signals and is fully protected against overloads and short circuits. It is widely available through distribution channels and is very inexpensive. The LTSR-6NP devices from LEM are wide-bandwidth closed loop Hall effect sensors. These sensors provide a voltage output that is proportional to the current flowing through the sense loop, with a transfer function of 312mV per amp [7]. This enables built-in visibility of the currents flowing in both the switch node as well as the inductor current. We have found that this visibility is essential in assisting student's understanding of circuit operation, especially with the non-linear and cyclical nature of switching regulator operation. Other voltage regulator boards that we have used in the past have required the use of expensive oscilloscope current probes to observe these currents; our system achieves these ends at a fraction of the cost.

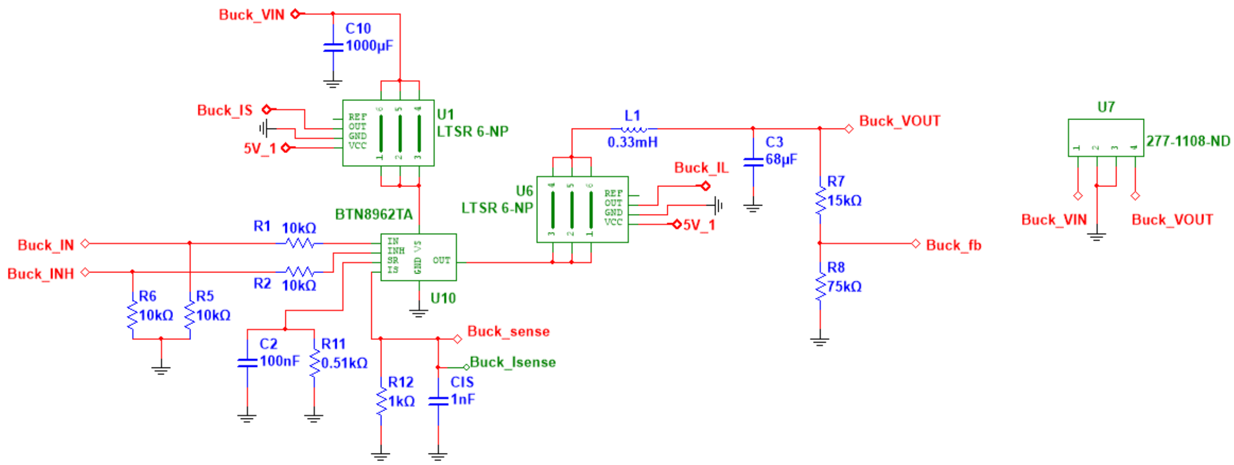

Figure 4 Buck Converter Schematic

The corresponding boost converter schematic is shown in Figure 5.

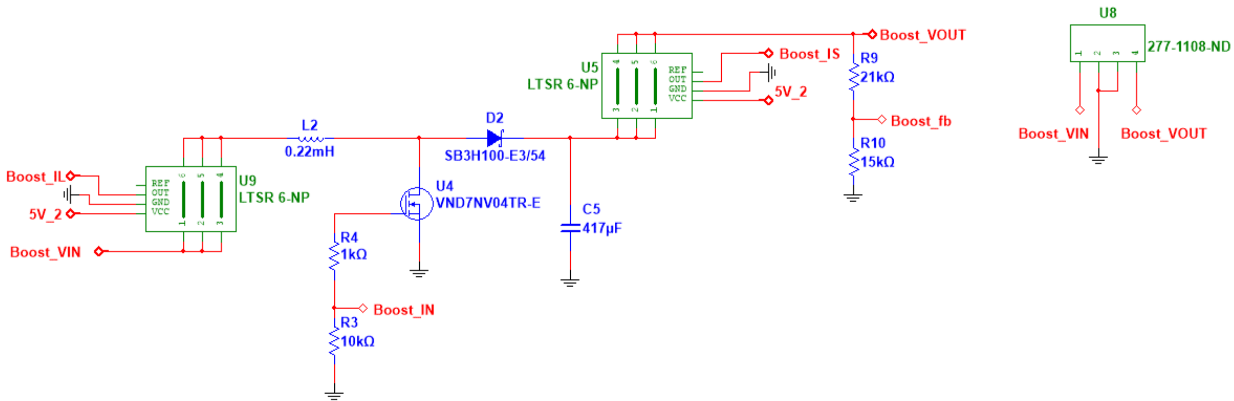

Figure 5 Boost Regulator Schematic

The current sense elements operate in the same fashion as for the buck regulator and provide similar information. The switch element is a VND7NV04TR-E from S.T. Microelectronics [8]. This device is fully protected against short circuits and overloads. As with the buck regulator, all control signals are obtained from the myRIO.

Control Logic

A unique feature of our device is that all control signals are derived from the embedded controller and are entirely controllable in software. The control program is written in LabVIEW™, and the high-speed control loops are run in the onboard FPGA, also programmed in LabVIEW FPGA [9]. The front panel and controls are shown in Figure 6. The same front panel control setup allows for control of either the boost or buck regulator sections without reloading the program. Unique features not found in commercially available units are the ability to set the switching frequency to any value up to 20 kHz, and also to run in manual mode where the user sets the duty cycle, or in a feedback configuration in which the control logic adjusts the duty cycle to correct the output voltage to a preset value.

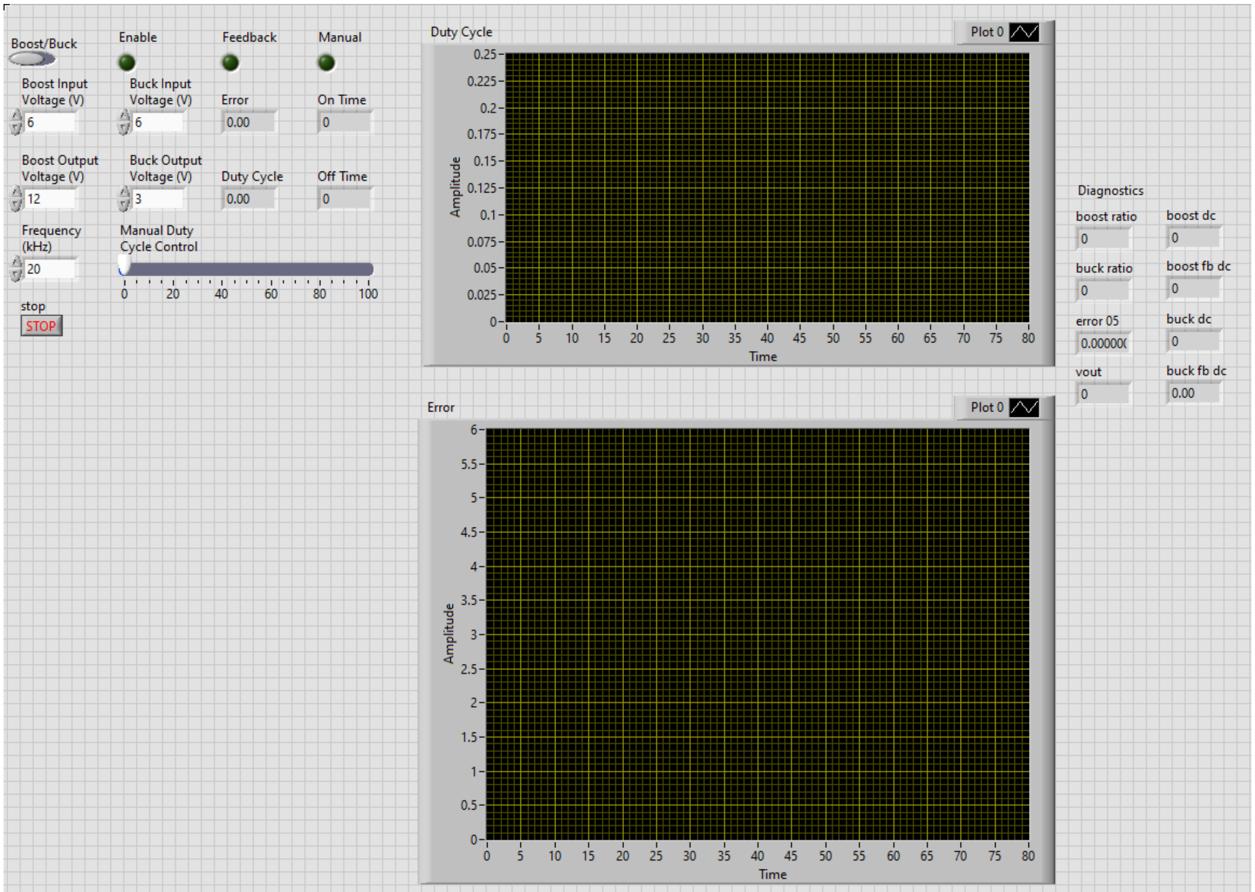

Figure 6 LabVIEW control front panel

This flexibility enables several experimental modes not previously available in commercial units. The manual mode allows students to study the ratio between input and output voltages and to vary both the input voltage and load independently of the duty cycle. This also enables the students to visualize how the feedback system would need to operate to adjust the duty cycle to match varying load conditions and input voltages. The ability to change the operating frequency enables students to study how switching rates affect inductor currents and overall efficiency.

In the feedback mode, a feedback loop is closed from the output back to the control logic, and the program adjusts the duty cycle to hold the output voltage constant in the face of varying load conditions or input voltage changes. The basic front panel in Figure 7 is shown operating in feedback mode, where the duty cycle is adjusting automatically to force the output voltage to match the target value. Note that a planned enhancement to this program also provides the user with the ability to vary feedback gain and modality to study the effects of stability and settling time. Again, by implementing all of the control algorithms in software, these changes are expedited compared to a hardware-only implementation.

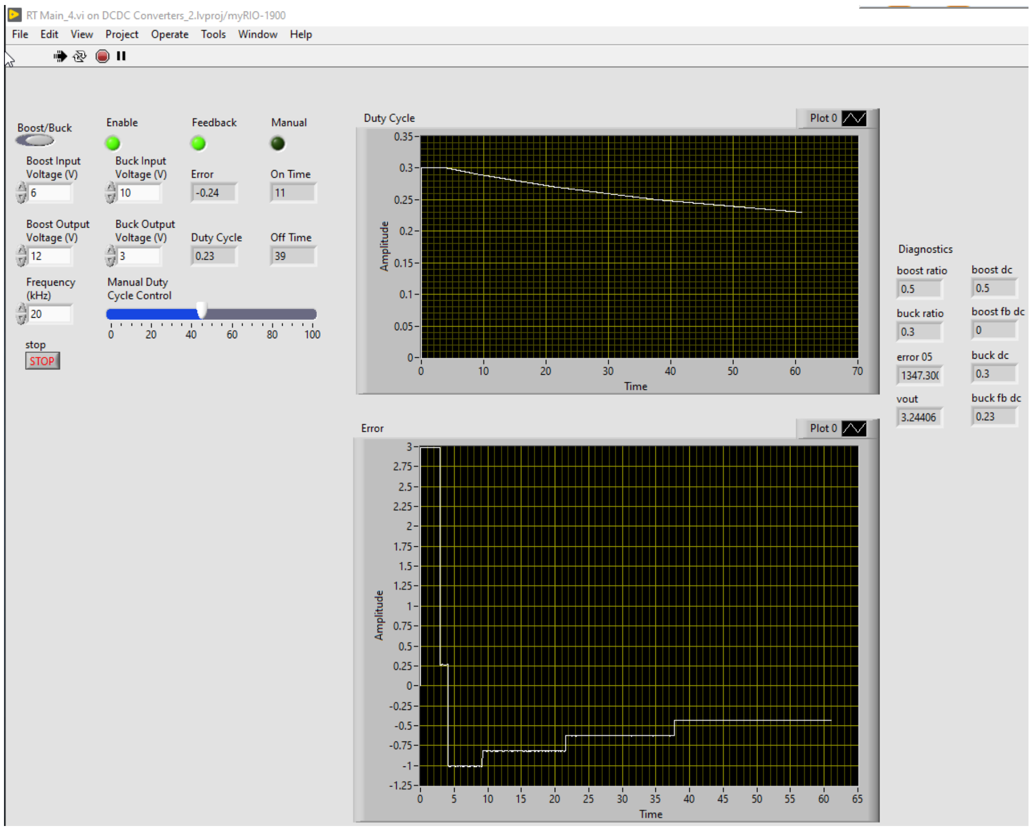

Figure 7 LabVIEW front panel in feedback mode

The basic block diagram is shown in Figure 8.

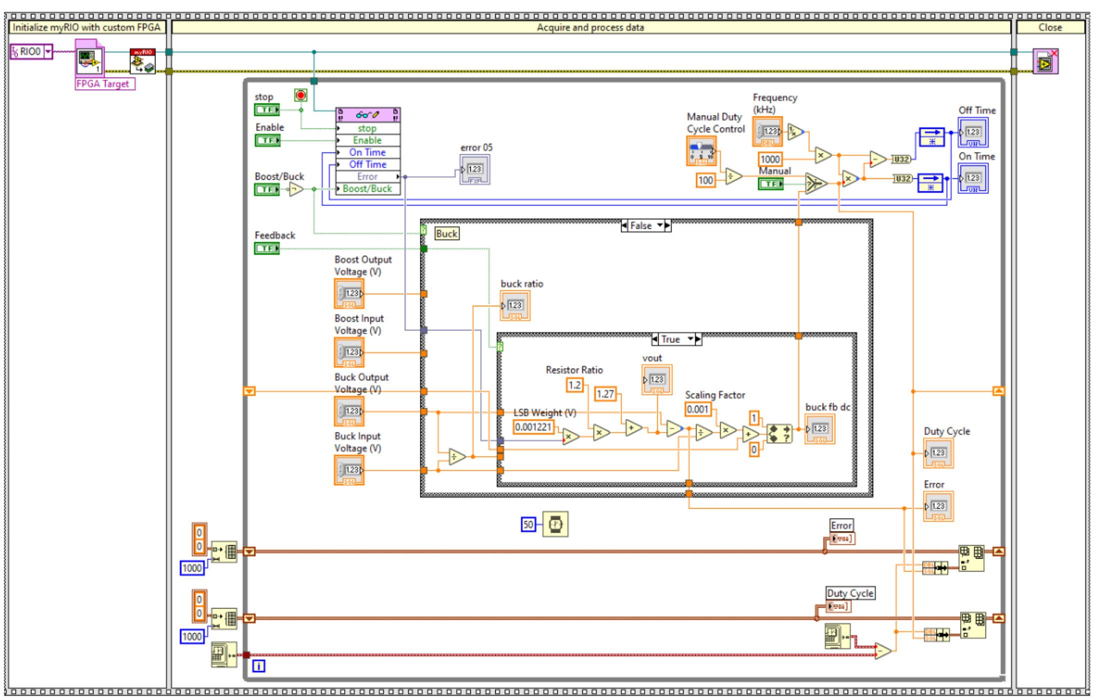

Figure 8 Block Diagram

Note that the flow of logic and data is simple and straightforward. This facilitates explaining operation to students with only minimal exposure to LabVIEW. It also exposes opportunities for students to experiment with different control loop techniques, examining stability, etc.; this is facilitated by the overload protection built into the hardware design.

Simulation

We have developed a companion simulation of the switching regulator system using the high-level functionality available in Multisim™ [10]. This enables our students to see functionality without getting bogged down in details.

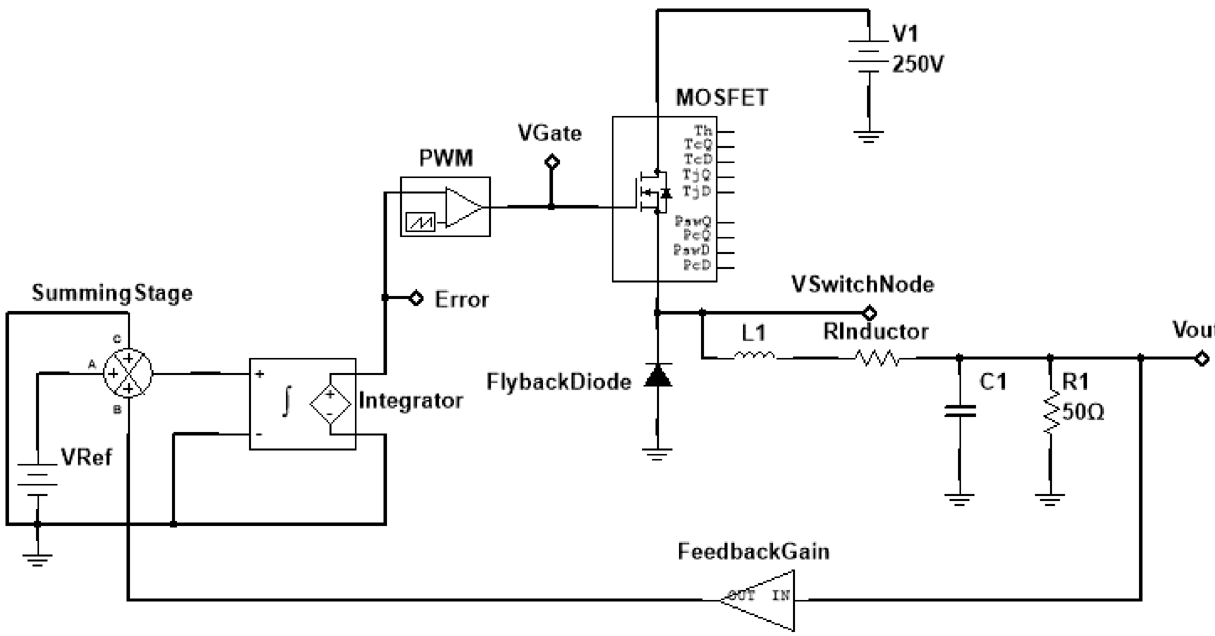

Figure 9 Multisim buck regulator simulation

The simulation of Figure 9 is for the buck section of the regulator. Note that all of the classical elements of a feedback system are clearly identifiable on the schematic, and we employ a class exercise to relate the high-level elements to the schematic in Figure 4.

A typical simulation for an input voltage of 250 volts and a regulated output voltage of 100 volts is shown in Figure 10. This simulation depicts the inductor current and output voltage during the startup and settling times of the voltage regulator circuit, and provide analogies to similar patterns observed on the actual board. This simulation also allows us to experiment with feedback gain and switching frequencies as well. The PWM waveforms are depicted in Figure 11. Here the students can study the relationships between the PWM duty cycle and the output voltage. Again, the high-level observations track well with the top-level types of information available through the graphical user interface and actual circuit board.

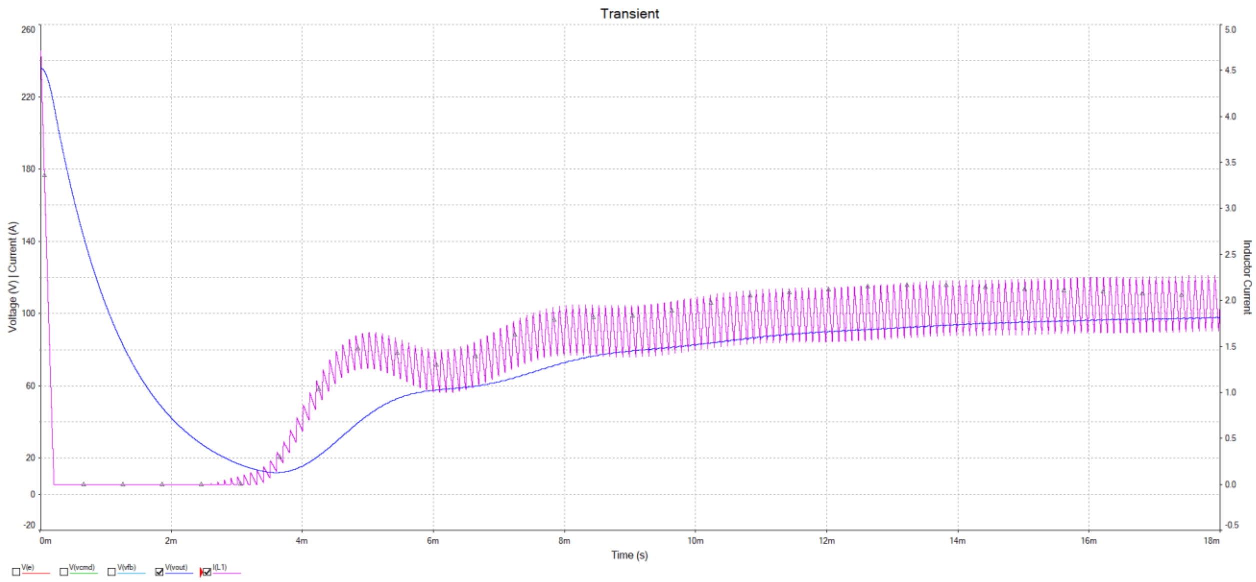

Figure 10 Simulation of output voltage and inductor current

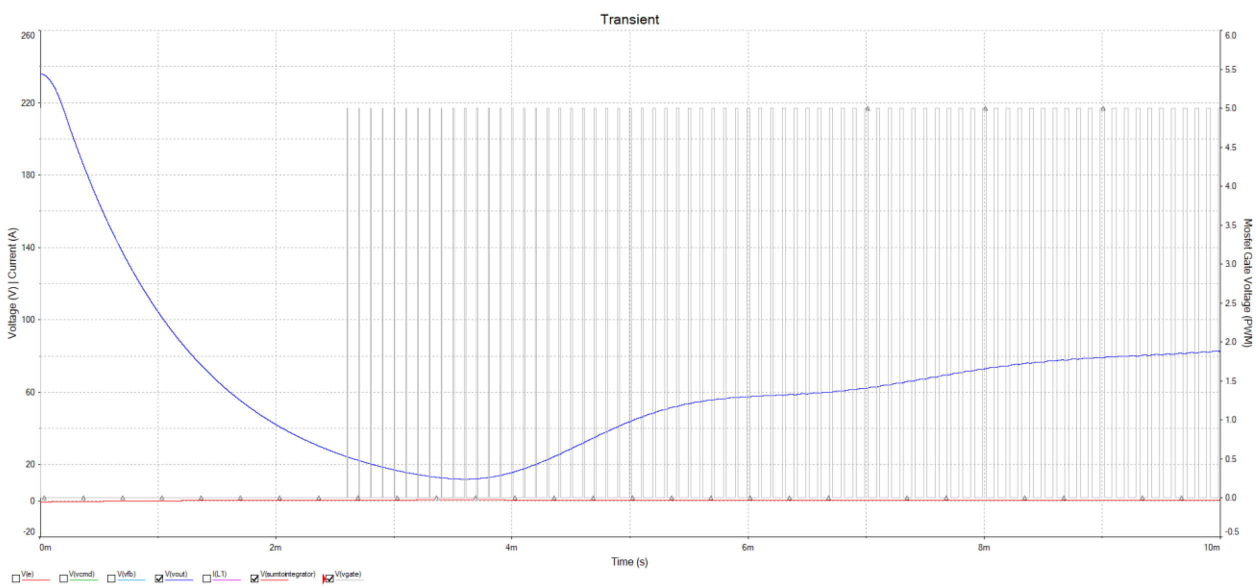

Figure 11 Output voltage and gate PWM drive

Classroom Scenarios

We employed this laboratory setup for the first time in the Spring of 2019 and expect to continue with it for the future. In our approach, a lecture was devoted to basic switching regulator theory for buck and boost regulators, followed by a lecture period dedicated to developing the high-level simulation for a buck circuit with feedback.

In the laboratory, we supplied power to the device from both a bench power supply as well as a photovoltaic panel. Students were allowed to adjust the switching frequency and duty cycle manually as well as run in feedback mode. Their response was extremely positive, and most students indicated that seeing both the simulation as well as the actual device in operation greatly enhanced their conceptual understanding of how the system worked.

Due to the flexibility of the design, however, the system could be employed in a pure power electronics class, where the focus is more on actual circuit operation. It could also be employed in a feedback controls course, where all of the electronics can be abstracted away, and the students are focused on stability, step response, and settling issues. It could also be employed as a building block in a renewable-energy focused course, with a focus on overall system efficiency.

Summary and Conclusions

We have presented a simple and inexpensive system for experiments with switching regulator systems, the heart of all electrical, renewable energy systems. The system is flexible and can be applied to various classroom scenarios and focus areas. Depending on student and class goals, this system may be employed for both high-level, abstract courseware as well as specific power electronics courses and controls related courseware.

As student demand for increased course coverage of renewable topics continues, we believe that experiments and hardware such as this are invaluable tools for developing baseline levels of comprehension. We see an understanding of the building blocks as a prerequisite for building a grasp of larger-scale system design issues.

The authors actively seek collaborations on projects such as this. All of our designs are open source, and we will provide full manufacturing and course materials.

References

[1] H. C. Powell and B. Hayt, “Developing a Low-voltage Microgrid for Experiments in Renewable Energy Distribution,” presented at the 2018 ASEE Annual Conference & Exposition, Jun. 2018, Accessed: Feb. 01, 2020. [Online]. Available: https://peer.asee.org/developing-a-low-voltage-microgrid-for-experiments-in-renewable-energy-distribution.

[2] “Power Management.” https://university.ti.com/en/faculty/teaching-materials-and-classroom-resources/ti-based-teaching-kits-for-analog-and-power-design/power-management-lab-kit-series (accessed Feb. 01, 2020).

[3] H. C. Powell, “BYOE: An Introductory Laboratory-Based Course on Switching Regulator Analysis and Design,” presented at the 2016 ASEE Annual Conference & Exposition, Jun. 2016, Accessed: Feb. 02, 2019. [Online]. Available: https://peer.asee.org/byoe-an-introductory-laboratory-based-course-on-switching-regulator-analysis-and-design.

[4] “TI Power Electronics Board for NI ELVIS III - National Instruments.” https://www.ni.com/en-us/support/model.ti-power-electronics-board-for-ni-elvis-iii.html (accessed Feb. 01, 2020).

[5] “myRIO Student Embedded Device - National Instruments.” https://www.ni.com/en-us/shop/select/myrio-student-embedded-device (accessed Feb. 01, 2020).

[6] I. T. AG, “BTN8962TA - Infineon Technologies.” https://www.infineon.com/cms/en/product/power/motor-control-ics/intelligent-motor-control-ics/single-half-bridge-ics/btn8962ta/ (accessed Feb. 01, 2020).
[7] “LTSR 6-NP | LEM.” https://www.lem.com/en/ltsr-6np (accessed Feb. 01, 2020).
[8] “VND7NV04 - OMNIFET II :FULLY AUTOPROTECTED POWER MOSFET - STMicroelectronics.” https://www.st.com/en/automotive-analog-and-power/vnd7nv04.html (accessed Feb. 01, 2020).
[9] “What is LabVIEW? - National Instruments.” https://www.ni.com/en-us/shop/labview.html (accessed Feb. 02, 2020).
[10] “Multisim - National Instruments.” https://www.ni.com/en-us/shop/select/multisim (accessed Feb. 03, 2020).