An Introductory Course In Energy Efficient Power Regulator Design

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Abstract

As interest in alternative energy resources increases it becomes necessary for undergraduates in Electrical and Computer Engineering to receive an introduction to efficient power control. In response to this interest, we have developed a studio style course in introductory switching regulator analysis and design employing industry-standard tools. The motivation for the material is accomplished through an introduction to conventional linear voltage regulators with an emphasis on their efficiency limitations. We then move to each of the basic topologies - buck, boost, and buck-boost. Class time is allocated to each depending on the complexity of the topology. Experiments illustrate the strengths and weaknesses of each system and are conducted in such a way that students can gain a basic understanding of the circuit and then proceed to more advanced topics, such as transient response.

Keywords

switching regulator, efficient power conversion

Background

Virtually all areas of study involving alternate energy resources must traverse a path that includes Electrical and Computer Engineering. Wind farms, photovoltaic arrays, and electric automobiles, to name a few, are all technologies that rely heavily on concepts related to switching voltage regulators and inverters as well as battery management. In a recent survey of second-year students in electrical and computer engineering at the University of Virginia, over 80% responded as being "likely" or "extremely likely" to be interested in an introductory course that would cover material about efficient energy conversion.

Existing courses in electrical power conversion and regulation have trended in several directions. In one case, the laboratory work is virtual or performed in a remotely connected scenario.[1,2] While these approaches are economical in space requirements, we believe that a strong interaction with hardware is very desirable for undergraduate electrical engineering students; they do not see simulation as "real." Other approaches that involve laboratory work require extensive equipment spaces that are not conducive to a studio teaching environment and are frequently very expensive.[3,4,5]

To address this interest and expand our elective offerings we have developed an introductory course in basic power electronics with an emphasis on voltage regulation. This course is a 1.5 semester hour elective course and is taught in a studio format, a method that has been very successful for us in other coursework.[6,7] From a pedagogical standpoint, our goal was to introduce students to the basic topologies most commonly employed in switching regulators, as those concepts are a core component of more advanced power control and delivery systems. A further goal was to have a strong hands-on component and to create an active association between expected results from simulation and tangible results from hardware. Also, due to space limitations we were constrained to come up with a course that would require a minimum of bench space and additional hardware. Finally, we wished to expose the students to some industry standard hardware and software that they would be likely to encounter in their professional careers. Additionally the students are required to keep a running log of all experiments performed in a virtual lab notebook format. Periodically throughout the semester students submit the current copy of the log and are asked for conclusions and explanations.

The balance of this paper will discuss our selection of hardware and software and our laboratory equipment setup. We will consider some additional low-cost hardware that we designed to facilitate some of the required measurements. We will also show typical experiments from throughout the course.

Laboratory Facilities and Hardware

A typical laboratory bench setup is shown in Figure 1. The space requirements are minimal, and we can make extensive use of existing equipment.

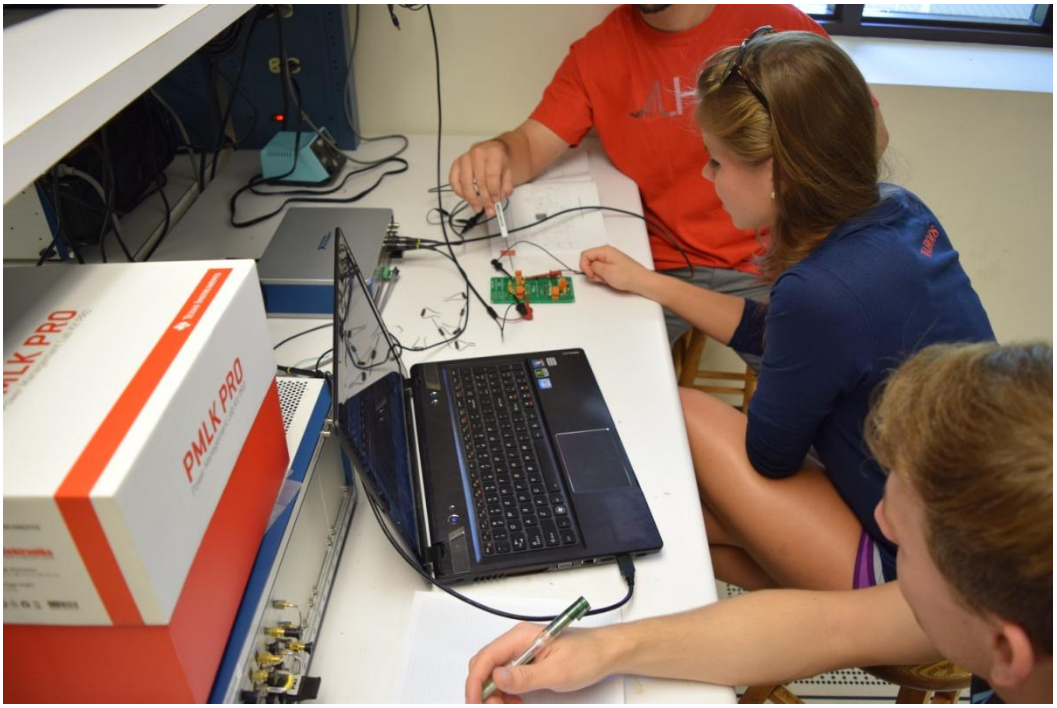

Figure 1 Basic Laboratory Bench Equipment

The capabilities of the National Instruments *VirtualBench* are leveraged to reduce further the space requirements.[8] This compact unit has a two channel 100MHZ Oscilloscope, Function Generator, triple output power supply and DMM. It interfaces directly to a laptop computer via USB and allows the students to record data for further analysis as well as visualize it in real time. This capability is also very useful as it allows students to move quickly from a simulation environment to a hardware one. It also enables us to share readily bench space with other classes.

In the example shown in Figure 2, we are sharing bench space for a power regulation class with a suite of laboratory equipment used for our wireless circuits class.

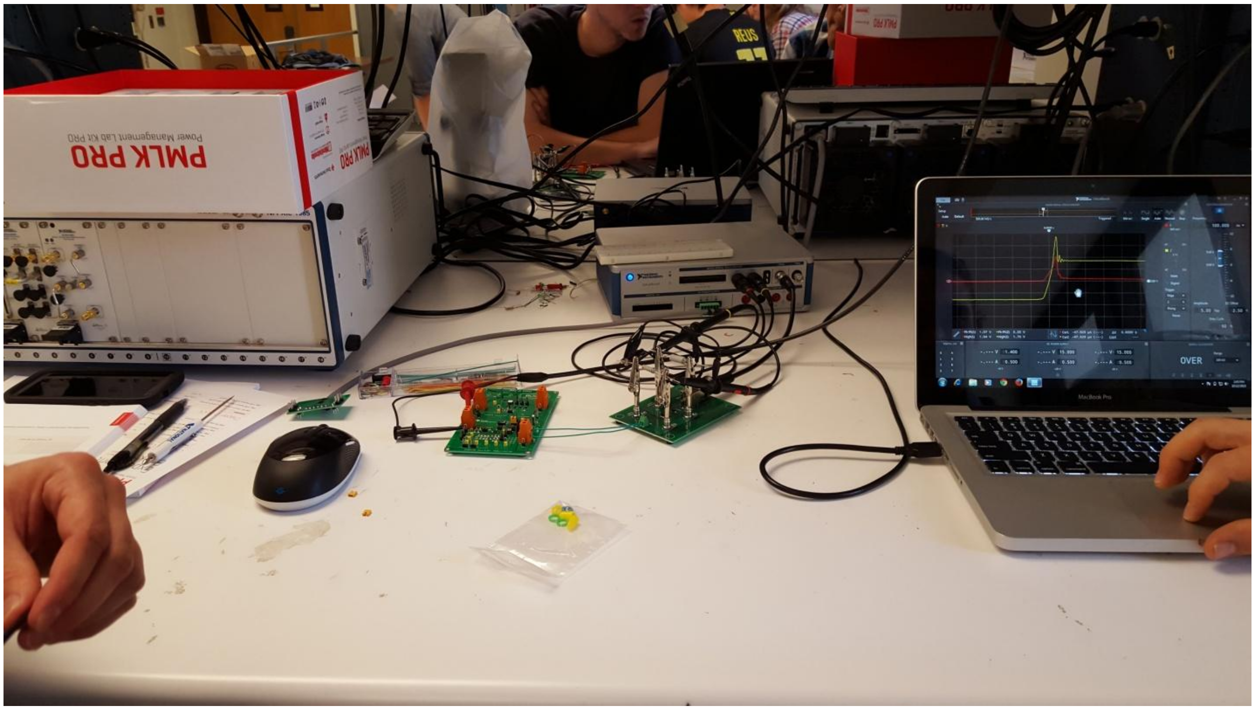

Figure 2 VirtualBench on shared bench top

The primary hardware employed is the PMLK Power Management Lab Kit from Texas Instruments.[9] This kit contains several basic non-isolated voltage regulation circuit boards in the most common topologies found in many power management designs. The suite of boards is shown in Figure 3.

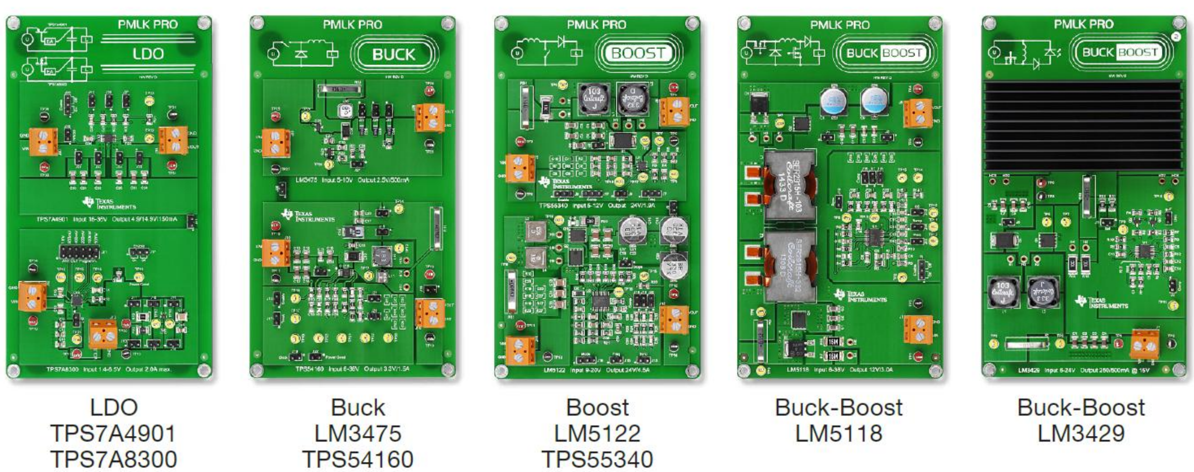

Figure 3 Voltage Regulator Kits (From svnq001.pdf available at ti.com)

Additionally a simple switching board for transient load response testing was developed. Commercially available electronic load testing devices are both bulky and expensive, and not deemed necessary for an introductory class.[9,10] For our course we felt that we could illustrate the concepts related to transient load response with a simple resistive switching device that would be both simple and flexible. The device is shown in Figure 4. The two pairs of alligator clips enable us to have one resistor that acts as a baseline load, and a MOSFET switches in the additional load with a signal derived from the function generator of the *VirtualBench*. The spacing is such that we can clip in a broad range of resistors to accommodate testing at virtually any combination of load resistance and power rating.

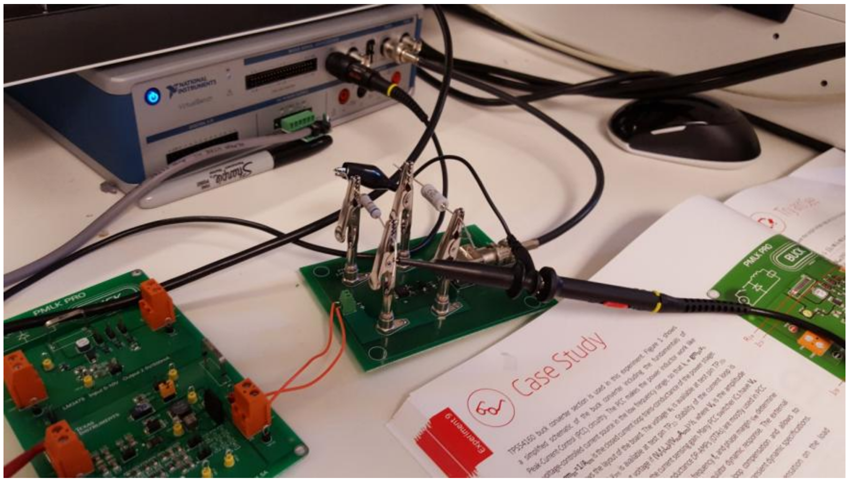

Figure 4 Assembled load switch

The switch is controlled by the signal generator on the *VirtualBench*, which facilitates synchronizing the oscilloscope display to the generated load step. It is also worthwhile to note that the gate circuit of the MOSFET includes a transient voltage suppression device that ensures that the circuit will be protected in the event of incorrect signal generator amplitude settings.

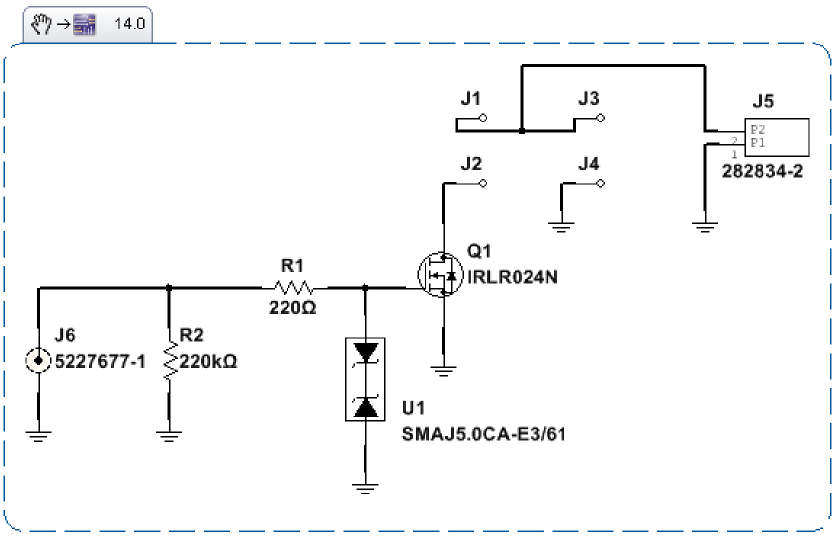

Figure 5 Load Switch Schematic

The schematic of the load switch is shown in Figure 5. It is extremely simple yet effective. The MOSFET can easily handle the currents delivered by typical bench power supplies and no further device protection is necessary. The students assembled their load switches, including soldering and testing as part of a class exercise.

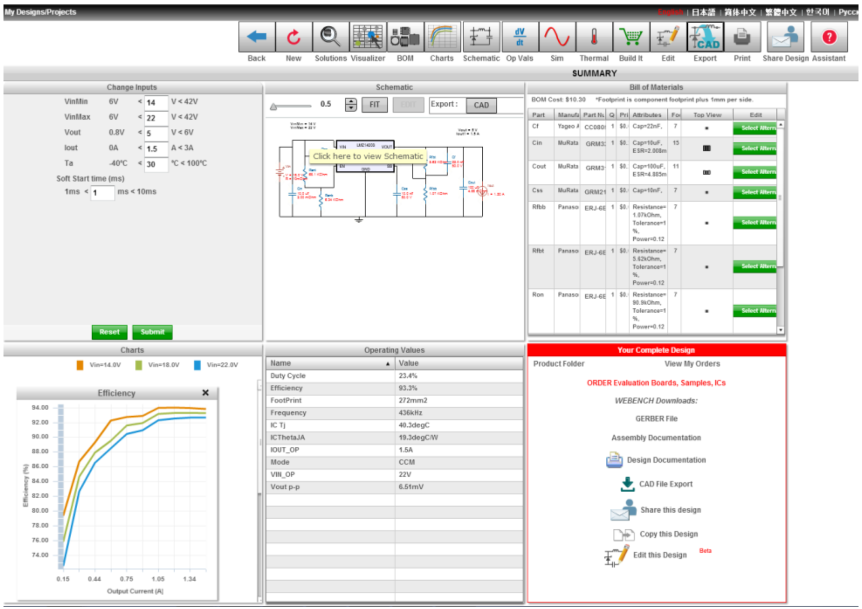

Figure 6 WEBENCH Design Screen

Simulation is also an important part of this course. There can be substantial differences between simulated results and the actual physical measurements on circuitry employed in switching regulators due to the effects of board layout and device characteristics. The *TI WEBENCH* on-line tool was extensively employed by the class as well.[11] This tool allowed us to directly compare theoretical versus observed results for each circuit and also allowed us to explore thermal concepts which are not easily quantified in a small undergraduate laboratory.

LDO Experiment

As an introduction to the concept of voltage regulation, we discuss the LDO (Low Drop Out) linear voltage regulator. The schematic from the version tested in class is shown in Figure 7 below. Of particular interest is the wide assortment of configuration shunt jumpers that allow for flexibility in constructing experiments under different operating conditions.

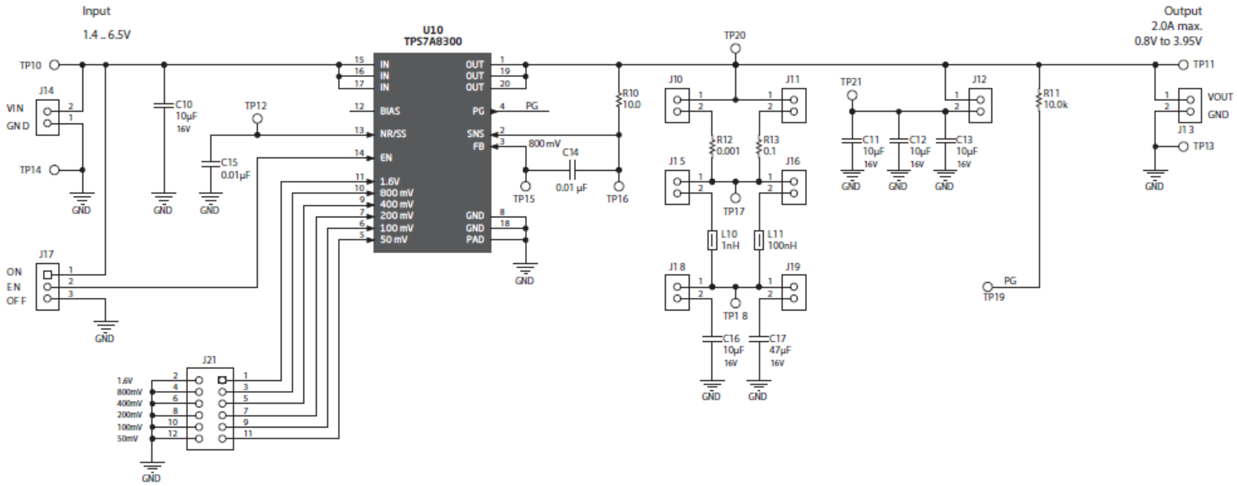

Figure 7 Schematic of LDO regulator (From PMLK kit)

Students are exposed to the basic theory including an introductory lesson feedback control. We then move on to test the device for efficiency and transient response. Students quickly gain insight to the relationships between input voltage and losses in the regulator as shown in Figure 8. They also study the transient response as shown in Figure 9. Facilities on the board allow the student to assess how the frequency compensation characteristics of the input and output elements and feedback network allow one to control the stability and transient response characteristics.

One of the insights that they develop is the notion that while an LDO regulator may have lower efficiency at high input voltage, the device has an excellent transient response and that when making design decisions a number of factors must be weighed against each other. This is an important engineering concept for them to grasp and easily demonstrated on the bench.

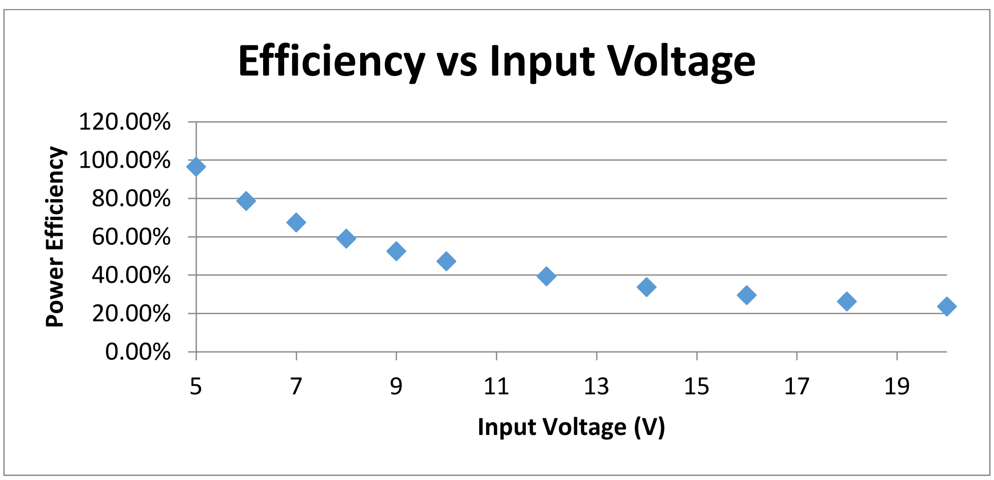

Figure 8 LDO regulator efficiency vs. input voltage

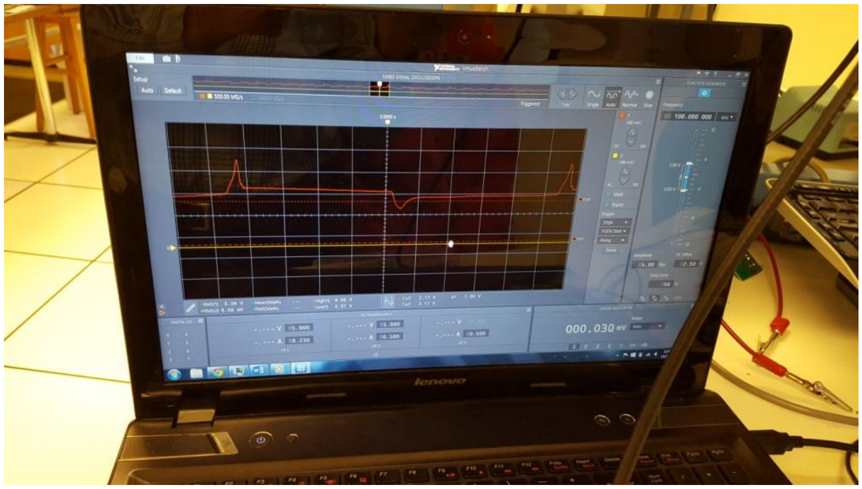

Figure 9 LDO transient response

Buck Regulator

One of the most common switching regulator technologies, and also one of the simplest to comprehend is the buck regulator, i.e. the input voltage must be higher than the output voltage. The schematic for the circuit tested is shown in Figure 10. The class studied the basic operating principles and waveforms and discussed the fundamental tradeoffs implied in the use of this technology. For example, they learned that there is always an inherent ripple component in the output voltage waveform, but counter to intuition, this ripple component is not a strong function of the load current. As with the LDO, we also look at efficiency and the students immediately grasp the gains possible as seen in Figure 11.

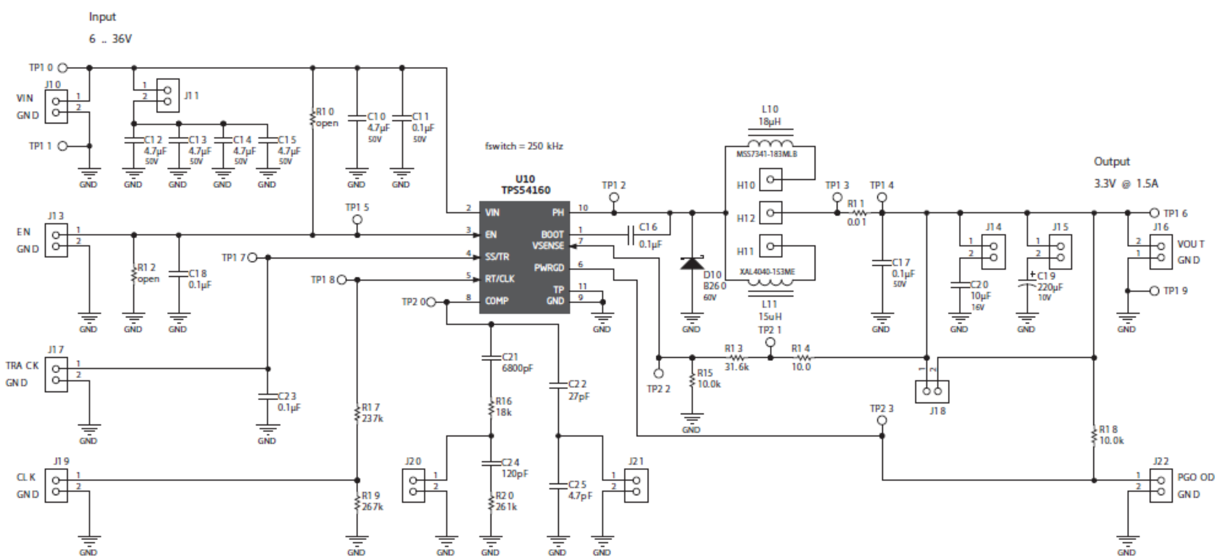

Figure 10 Buck regulator schematic

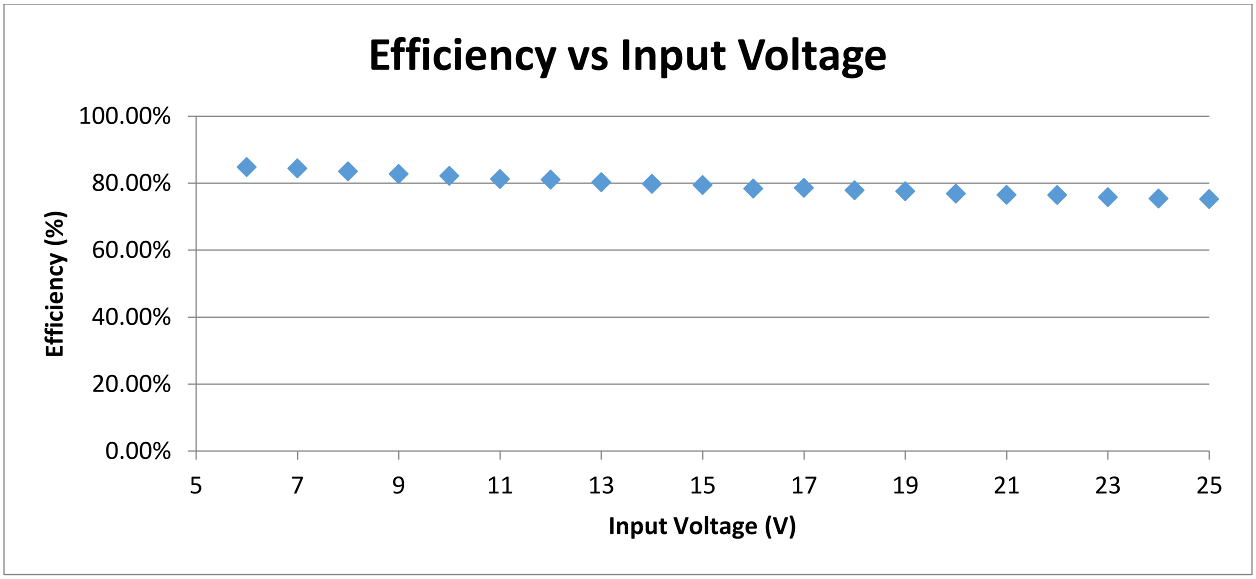

Figure 11 Efficiency vs. input voltage for a buck regulator

As with the LDO, there is an abundance of configuration shunt jumpers that allow the students to examine the effects of the feedback network, inductor values, and output capacitance on ripple, transient response, and voltage regulation.

Students observe critical nodes in the circuit to correlate simulation results with experimentally obtained values. For example, in Figure 12 below, the student is observing the switch node waveform, TP12 in Figure 10, and studying how duty cycle varies with the input voltage.

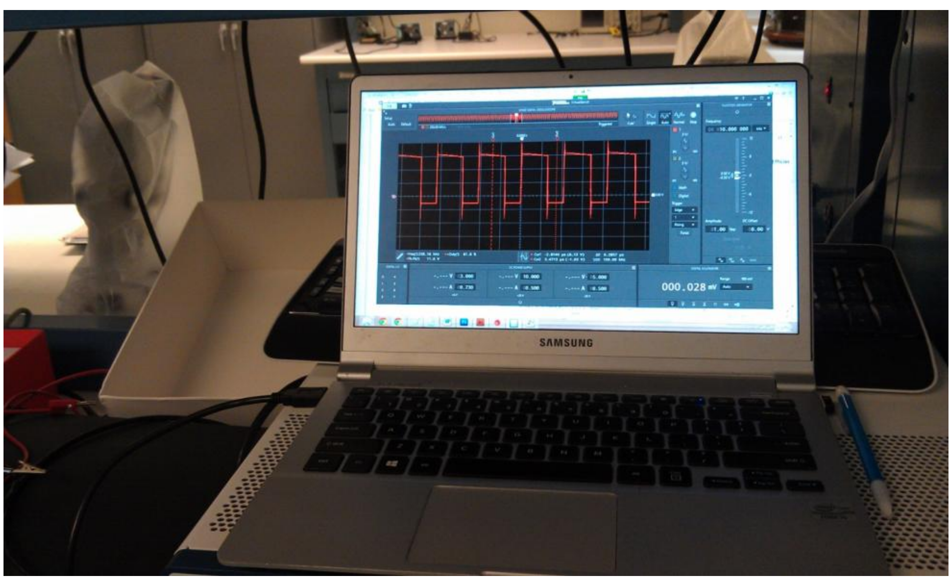

Figure 12 Switch node waveforms

Students also study transient response and immediately become aware of the effect of the inductance and output capacitance as well as feedback compensation on the overall transient response, which is usually somewhat slower than an LDO regulator.

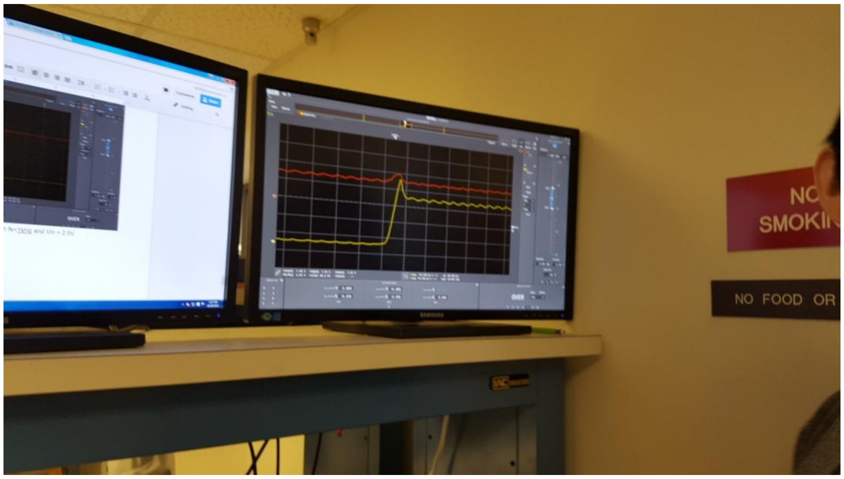

Figure 13 Buck regulator transient response.

Other regulator topologies

In addition to the LDO and Buck technologies, we also studied boost, and buck-boost technologies, The experimental setup, and tests performed were very similar in each case. In particular, the applications areas of each were explored, and students discussed scenarios of how each might be applied. For example, in low-cost battery-operated systems that run infrequently, i.e. a door sensor in a home burglar alarm system, an LDO might well be the best overall choice due to its relatively good response time and low costs. A requirement would be that the battery voltage would by necessity be somewhat higher than the circuit operating voltage. Alternatively, when operating a modest power system from a highly variable source such as a photovoltaic array, a buck-boost topology might be the best suited.

In the conclusion of the course, we examine design examples of different technologies and study the relative merits of each. It is through exercises such as this that the students gain insight into both the minutiae of operating principles, but also larger picture design issues and tradeoffs.

Summary and Conclusions

We have demonstrated a low-cost laboratory setup suitable for an introductory switching regulator operation and design course appropriate for upper-level students in electrical and computer engineering. Of particular note is the compact space requirements of the *VirtualBench*, and the availability of a standard set of test boards from Texas Instruments. The laboratory experience was further made possible by the load testing boards that we designed. (The author can make the plans available for others.)

We believe that with the increasing importance of renewable energy sources that it becomes necessary for electrical and computer engineering programs to stay abreast of the relevant technologies. Also, we believe that it is crucial for students to receive instruction in a blended format that combines lectures with simulation and hardware laboratory experience. We anticipate expanded versions of this course in the future as we seek to broaden our undergraduate experience.

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