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Designing Introductory, Hands-on, Open Source Power Electronics Lab Exercises

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Designing Introductory Hands-on Power Electronics Lab Exercises

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Abstract

There are numerous challenges in designing power electronics lab exercises that illustrate textbook concepts on the lab bench, at low cost, and requiring only basic test equipment. For contrast - it is possible to illustrate signal processing concepts by building a slow, stable circuit on a breadboard, and scaling to higher frequencies on paper, once the concept is understood. But this model is difficult to apply even to the most basic power conversion circuits; while signal processing functions are often available as discrete components, most modern power circuits are highly integrated out of necessity. While it is possible to base a lab exercise on an off-the-shelf monolithic power converter, much of the operation is hidden, and quality oscilloscopes and current probes are out of reach for many schools. This paper presents the development of several hands-on lab exercises in power electronics that are designed to provide hands-on, intuitive experience with concepts such as thermal resistance, efficiency, inductor current waveforms, and operation of boost and buck converters, early in a student's academic career. Emphasis is placed on simplicity, low-cost, and exposing concepts, over electrical performance. An open-source model for distribution, review, and improvement is followed, and examples of improvements made as a result of student experience in the lab are given. Experience learned from conducting two workshops at Cal Poly State University helped us indicate areas of improvements. Results of initial assessments from the latest workshop demonstrate that the materials, organization, time-allotted, and pace of the workshop are at the appropriate level. The lab kits used in the workshop provide the students with valuable hands-on exercises while enforcing a deeper understanding of concepts learned in class. More assessments will be conducted in future workshops and long-term assessments will also be conducted based on student course selection in subsequent quarters, and ultimately, students' choice of technical elective courses.

Introduction

Analog Devices Inc. (ADI), like many other power semiconductor companies, employs electrical engineers with a broad spectrum of skills for roles in semiconductor design, applications, testing, and support roles. These positions are filled with a high percentage of new college graduates, and hands-on experience is weighed heavily when interviewing. To this end, the company has long provided a free and open-source curriculum of "Active Learning" lab exercises on topics from basic circuits to data conversion to communications and software defined radio [1-2] that is used by various schools to augment their existing programs. In addition, the company has been supporting local universities in enhancing their electrical engineering programs [3-4], incorporating learnings from these collaborative efforts into new exercises.

The power electronics section of the Active Learning curriculum was lacking in content, so a new effort was started in 2017 to address this gap. Since this effort was starting from scratch, it was decided that lab material would be tested at local universities in a workshop setting as it was being developed, in an effort to maximize quality and minimize potential pitfalls and student frustration. Furthermore, power circuits are generally not compatible with solderless breadboards, so considerations for the design of low-cost printed circuit board modules will be detailed.

At many institutions, introductory power electronics courses are lecture only, without a formal lab. A goal of these experiments is to lower the barrier to entry for providing direct, hands on lab experience with power circuitry to help students relate abstract equations from lectures to the real-life phenomenon that they describe [5].

Experiment 1: Switched Capacitor Power Supplies

One of the first concepts involving energy storage that a student learns is the idea that a capacitor can store charge, and hence energy. Note that the *mechanical* energy storage mechanisms that are studied in first-year physics classes can be demonstrated with examples with which the student has had "real world" experience: squeezing a spring, spinning up a bicycle wheel by turning pedals by hand, etc. For learning and developing intuition about *electrical* energy storage and transfer, capacitors have some nice properties:

- The storage is static – that is, you can store energy by charging the capacitor, hold it in your hand for a "human perceptible" amount of time, then discharge it sometime later.
- It is easy to accurately measure the energy content with low-cost test equipment – It is trivial to measure a DC voltage to an accuracy of better than 1%, and while the initial tolerance on large capacitors is typically quite large, measuring the time-domain response of the capacitor in an R-C circuit will easily produce values accurate to a few percent if a capacitance meter is not available.

The popularity of switched capacitor power converters has varied over time; it provides a convenient way to double and invert voltages at low power levels, one formerly ubiquitous example being the generation of bipolar 10-12V rails required for RS232 ports on computers in the 1970s to 2000s. These rails were often "borrowed" for other circuitry – to provide a supply for an op-amp in an analog front end, for example. New developments in 48V bus to sub-1V processor core applications find high-power switched capacitor circuits used in intermediate stages, as a fixed ratio voltage reducer followed by a traditional buck final stage.

An experiment was therefore designed to provide hands-on experience with capacitors as energy storage and energy conversion elements. More specifically, the first experiment in the new series of power electronics exercises is on a switched capacitor converter using LT1054.

Experiment Highlights

The Active Learning Switched Capacitor experiment starts out very simply – with a human-controlled voltage doubler and inverter as shown in Figures 1 and 2.

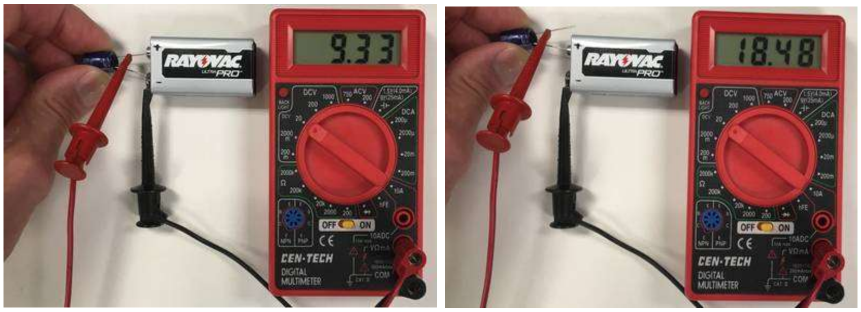


Figure 1: Human-controlled voltage doubler.

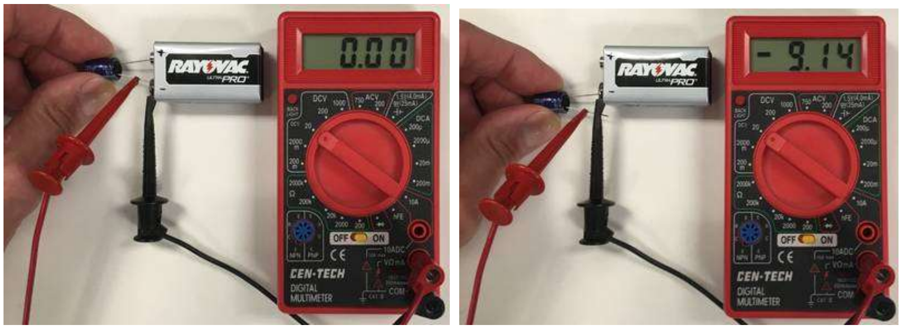


Figure 2: Human-controlled voltage inverter.

It then goes on to simulate a close-to-ideal switched capacitor inverter and doubler in LTspice, a freely available analog circuit simulator [6]. An important learning aspect of this (and subsequent) exercises is the use of close-to-ideal switching elements in LTspice when concepts are first introduced. Simulations using idealized components allow a direct comparison with textbook formulas; in this case, conservation of charge. In general, using truly ideal components will result in long simulation times or simulations that fail to convergence. But parasitics can be kept very small, allowing the simulation to approach ideal behavior. The experiment then goes on to detail the construction of an inverter and doubler based on the LT1054, a switched-capacitor power converter with a slow (25kHz) switching frequency that is compatible with solderless breadboards.

The cost of materials for this experiment is less than US$10, assuming an oscilloscope is available and that students have their own breadboards. Capacitor values are noncritical, any value between 47µF and a few hundred microfarads, with a 25V or higher rating will work.

Experiment 2: Efficiency and Power Loss

Undergraduate electrical engineering course requirements do not typically include courses on heat transfer, which, while critically important for electronic design, gets left behind. And the basic concept of “how hot is a watt?” used to be taught implicitly through everyday experience – It only takes once to learn that you cannot touch a 100W, or even a 60W incandescent light bulb, but a 7.5W night light bulb is uncomfortable but tolerable. Nowadays, a qualitative intuition about power dissipation and thermal management comes first from feeling how hot components, circuits, and enclosures get while in operation. But this qualitative experience may never be backed up with quantitative measurements, until the student is in industry and is forced to address an overheating circuit. An experiment was therefore designed to expose the student to basic measurements of temperature, temperature rise due to power dissipation, thermal resistance, and the relationship between power loss and efficiency.

Experiment Highlights

The experiment utilizes a linear type voltage regulator (LT3080) since its power dissipation can be accurately calculated by measuring the voltage drop from input to output, and the output current. A heat sink with a specified thermal resistance is attached to the regulator to help dissipate the generated heat as shown in Figure 3.

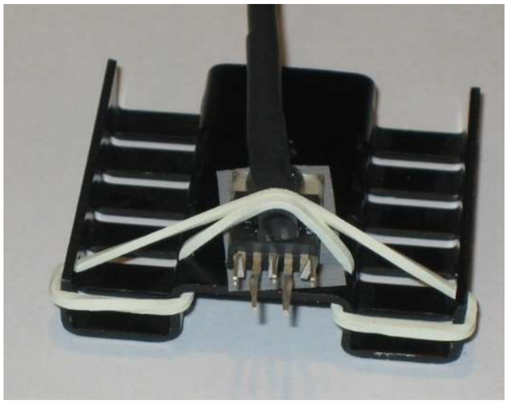


Figure 3: LT3080 mounted to heat-sink, with AD595 temperature sensor.

The composite thermal resistance of the package and heat sink is then modeled as an electrical circuit and simulated in LTspice. Several data points are taken on the experimental setup, measuring temperature rise of the top side of the case for different power dissipations. Students' results are typically within 10-15% of the theoretical thermal resistance provided in the datasheet, which is surprisingly close given the simplicity of the experimental setup, and the variability in factors such as glue thickness between the sensor and package, thermal interface between the regulator package and heat sink, airflow, etc. The experiment then goes on to measure the efficiency of an LTM8067 switching type regulator as shown in Figure 4, demonstrating that its temperature rise is negligible compared to the linear regulator counterpart LT3080.

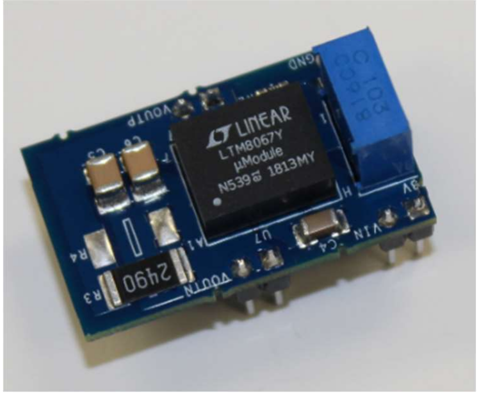


Figure 4: LTM8067 Flyback Converter Assembly.

The experiment was designed around materials included in a US$45 parts kit, but it is adaptable to materials on hand. Almost any linear regulator and heat sink will work, provided datasheets with thermal resistance are available for both. The LTM8067 breakout board is a custom-built assembly specific to this parts kit, but there are low-cost alternatives, such as an automotive phone charger, which is essentially a 12V to 5V switching buck converter.

Improvements

The first time that this experiment was run in a workshop, rubber bands were used to hold the temperature sensor against the linear regulator. This posed a problem since it would take numerous tries to get the band placed just right and document. While all students eventually got their experiments running, this was clearly a weak point. The solution for the subsequent workshop is to use Cyanoacrylate glue (super glue). While cyanoacrylate is incredibly strong in tension, it is weak in shear; thus, the TO-92 package temperature sensor can easily be twisted off with pliers and reused.

Experiment 3: Buck (Step-Down) Converters

While linear regulators are relatively easy to use and understand, at least in terms of principles of operation, efficiency, and power dissipation, switching regulators represent the majority of power conversion circuits. An experiment was therefore designed to illustrate key principles of switching regulator with buck or step-down converters, using circuitry that exposes all interesting circuit operating waveforms. The core of this exercise utilizes the LT1054 from the aforementioned switched capacitor experiment and a 6-winding coupled inductor. As with the switched capacitor lab, this exercise begins by deriving key equations, and showing the relationships in LTspice. The actual circuit as shown in Figure 5 is then simulated, accounting for the non-idealities of the components.

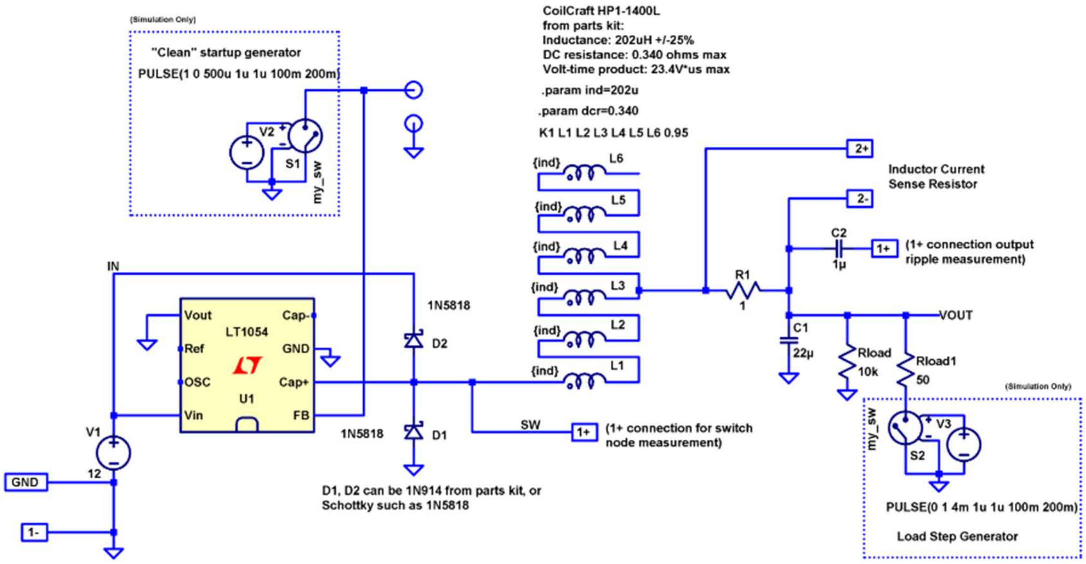


Figure 5: Open-loop Buck Converter Simulation.

The simulation can be configured to step through the inductor taps, clearly showing the relationships that: A higher inductance will have a lower ripple current, and hence lower output ripple voltage. However, the increased series resistance results in a higher voltage drop as depicted in Figure 6.

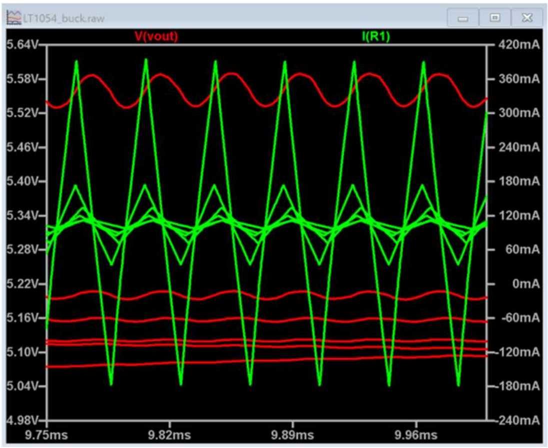


Figure 6: Simulated Inductor ripple current and output voltage for 1 to 6 inductor taps.

The next step is to reinforce the concepts learned in the simulation by building and measuring the circuit. Figure 7 shows construction details. The prototype circuit was built on a PermaProto solder breadboard for durability, but can be constructed on a solderless breadboard as well.

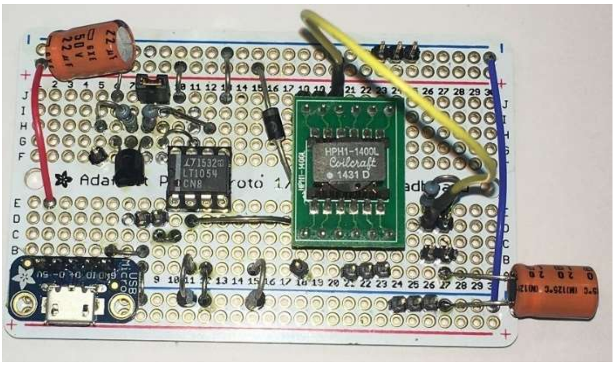


Figure 7: Construction.

Another key aspect of this circuit is that only basic test equipment is required. Figure 8 shows the switch node voltage and inductor ripple current, measured with an ADALM2000 software defined instrument. Nearly any benchtop oscilloscope with a 1mV/division vertical resolution can be used for these measurements, but if one is not available, the ADALM2000 provides a US$150 solution.

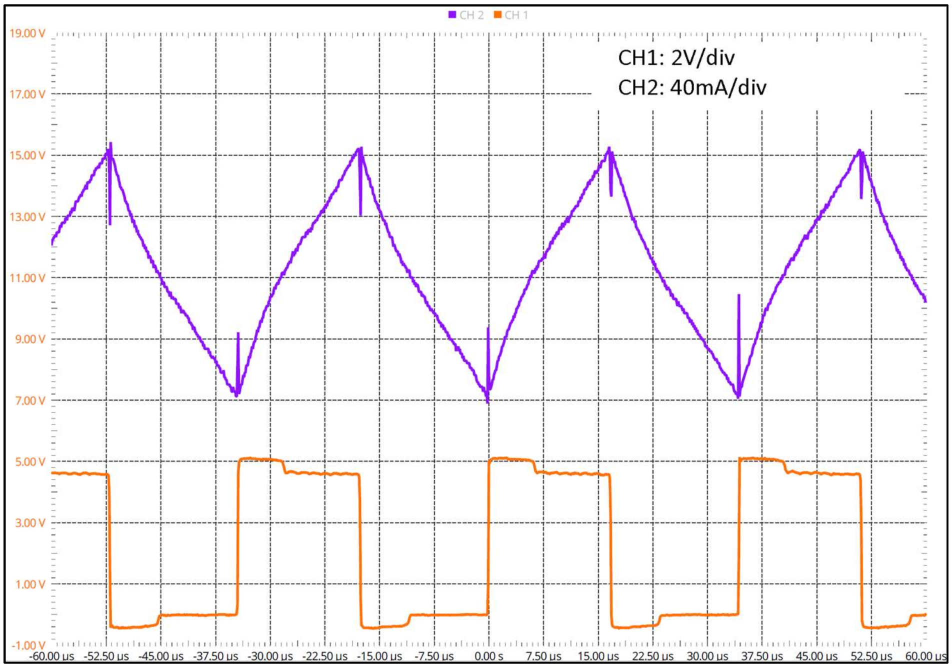
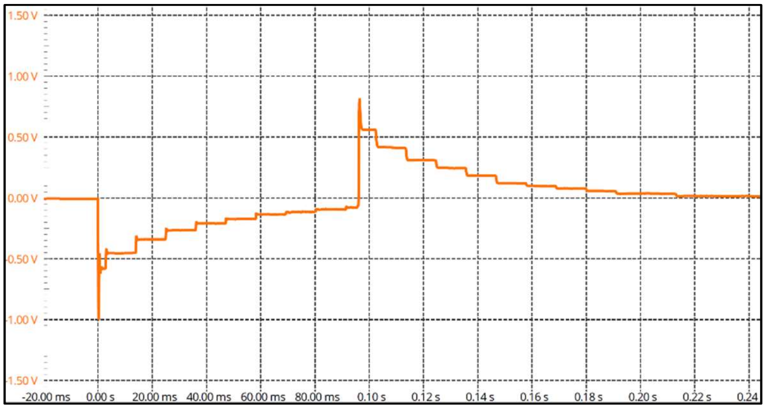
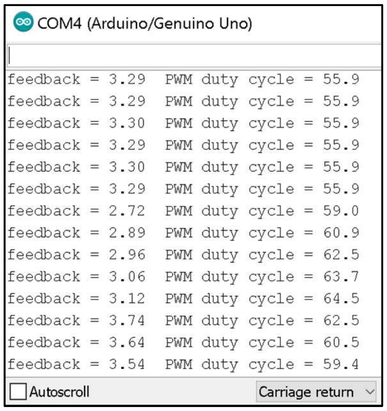


Figure 8: Ripple Current and switch node waveforms.

The exercise then goes on to measure open-loop load regulation by introducing a 50-ohm load, and noting the drop in output voltage. An Arduino microcontroller is then used to implement a simple (but functional) voltage feedback loop, with the measured feedback voltage and the calculated duty cycle that is sent to the PWM output reported to the serial terminal. Arduino is ubiquitous among students (and professional engineers), and its use is a way of using a familiar tool to accomplish a task in the analog world. Figure 9a shows the transient load-step response of the closed loop converter, and Figure 9b shows the Arduino’s serial output during the transient.





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feedback = 3.29  PWM duty cycle = 55.9
feedback = 3.29  PWM duty cycle = 55.9
feedback = 3.30  PWM duty cycle = 55.9
feedback = 3.29  PWM duty cycle = 55.9
feedback = 3.30  PWM duty cycle = 55.9
feedback = 3.29  PWM duty cycle = 55.9
feedback = 2.72  PWM duty cycle = 59.0
feedback = 2.89  PWM duty cycle = 60.9
feedback = 2.96  PWM duty cycle = 62.5
feedback = 3.06  PWM duty cycle = 63.7
feedback = 3.12  PWM duty cycle = 64.5
feedback = 3.74  PWM duty cycle = 62.5
feedback = 3.64  PWM duty cycle = 60.5
feedback = 3.54  PWM duty cycle = 59.4
```

(a) (b)

Figure 9: (a) Closed-loop load step transient (b) Arduino Output.

Improvements

This experiment was first run at Cal Poly State University in November 2018, using partially assembled modules built on Arduino prototype shields. Assembly was done by hand, with the inductor connections left to the student to make on a miniature breadboard during the workshop. The main purpose of this exercise was to vet the experiment itself, but obviously hand soldering is not repeatable or scalable. An Arduino “shield” form factor PC board module was subsequently designed and manufactured, shown in Figure 10. This module facilitates running all experiments in the exercise, without the overhead of constructing and debugging the circuit itself. It can be installed directly on an Arduino Uno, and 25-mil post style test points are compatible with the ADALM2000 and other low-cost, USB oscilloscopes.

Figure 10: ADALM-BUCK module.

This provides three methods of running this experiment:

- If low cost is a concern, students are familiar with breadboarding, and time for debugging is available, then the breadboard approach is viable, and all components are included in the US$45 parts kit mentioned in Experiments 1 and 2.
- Students familiar with soldering can fully or partially assemble the experiment on an Arduino prototyping shield, again, with parts taken from the parts kit.
- The PC board module can be used if time is a concern or students are less familiar with bread-boarding. This board lists for US$30, and can be re-used multiple times.

Experiment 4 and beyond: Complete Buck and Boost Regulators (In Development)

The next natural topics to cover are buck and boost converters that follow conventional topologies (in contrast to the somewhat contrived LT1054-based buck experiment.) The buck basics experiment pushes the practical limits of circuit complexity that can be built on a breadboard. Furthermore, higher operating frequencies, higher currents, and small current sense voltages further preclude the use of breadboards, thus a printed circuit board becomes a necessity.

A switching regulator module was therefore developed with the following functional requirements and design directives:

- Demonstrate the operation of non-synchronous buck and boost converters
- Operation in open-loop duty cycle control and open-loop peak current control modes
- Operation in closed-loop voltage mode and current mode
- Use discrete circuit elements such that all control nodes can be accessed
- Require only low-cost instrumentation (USB oscilloscopes, economy multimeters)
- Protection from overvoltage/reverse voltage connections
- Integrated load bank with thermal protection

There were no specific electrical performance requirements on this design (efficiency, power level, voltage range, etc.), the primary design directive being the clear exposure of concepts.

Figure 11: Prototype in operation.

Experiment Highlights

One of the first experiments is to measure the relationship between Duty Cycle and voltage increase (boost) and decrease (buck) factors by manually adjusting duty cycle. This is generally not directly possible with an integrated circuit implementation, as the duty cycle is controlled by internal nodes. In this circuit, frequency, duty cycle, and peak current limit are independently adjustable, allowing exploration of all modes of operation. Another experiment is to demonstrate the relationship between number of windings and current required to saturate the core of the inductor used in the module. This is achieved by choosing the inductor to have small enough core size such that saturation can easily be demonstrated, as shown in Figure 12.

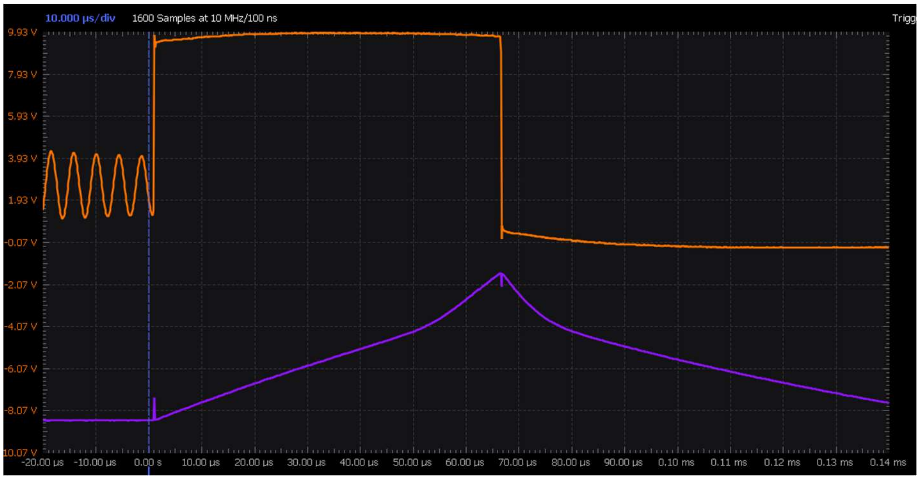

Figure 12: Inductor saturation

Other experiments in development include:

- Measurement of the power path frequency response
- Design of error amplifier compensation networks
- Verification of closed-loop response using onboard circuit implementing Middlebrook's method.

These exercises will be tested by 3rd and 4th year electrical engineering students in a workshop forum in Spring, 2020.

The target list price for this board is between US$75 and US$100, with the goal that only very basic additional equipment is required (multimeters, medium-bandwidth oscilloscope, variable power supply).

Assessment

The Efficiency/Power Loss and Buck Basics lab exercises were delivered as 4-hour workshops at Cal Poly State University in November 2018, May 2019, and November 2019. The November 2019 workshop consisted of a group of 26 first-year students, working in groups of 3. All successfully completed the exercises, then completed surveys, with the results shown in Table 1.

Table 1. Survey Results.

Question	Average	Std. Dev.
Workshop objectives were clearly defined	4.000	1.069
Workshop objectives were overall met	4.531	0.618
The difficulty of this workshop was appropriate	4.063	1.181
The time allotted for the workshop was sufficient	3.938	0.929
The material was presented in an organized manner	4.438	0.892
The pace of the workshop was appropriate	4.563	0.814
The activities in this workshop gave me sufficient hands-on practice	4.688	0.602
The lab kits / modules helped me understand the concepts	4.344	0.870
Given the topic, this workshop was: (1-too short, 3-too long)	1.719	0.446
In your opinion this workshop was: (1-intro, 2-interm., 3-advanced)	1.719	0.682
Please rate the: (1-5 = poor, fair, good, very good, excellent)		
a. Instructors	4.813	0.403
b. Handouts	3.875	1.025
c. Lab kits / modules	4.500	0.817
d. The workshop overall	4.563	0.727

The students were not expected to understand the theory behind these circuits ahead of time. On the contrary, the objective was to challenge the student with concepts that they may not understand at all, but presented in a way that allows them to touch, feel, and measure operation with their own hands.

The rating of 1.719 for the question “was this experiment intro, intermediate, or advanced” is telling – first year students viewed the material as between intro and intermediate, even though the idea of inductor current ripple is not introduced until they enter the second year, and a typical electrical engineering student may never encounter thermal resistance calculations. This would indicate that these concepts were presented in an easy-to-grasp way, with the hope being that when these concepts are more readily understood in detail when they are encountered in class.

The long-term impact and effectiveness of these exercises will require follow-up surveys asking:

- Did this experience influence your choice of subsequent classes in your undergraduate electrical engineering program?
- Did this experience influence your choice of major or concentration?
- Did this experience influence your choice of whether to pursue a master’s degree?

Open-Source Considerations

One common aspect of all of the University Program Active Learning material, including the exercises in this paper, is that they are open-source. Open Source has a clear definition in the software world, with several commonly employed licenses [7]. In the context of Active Learning material, Open Source allows users and academics to use the material free of charge, and to adapt, improve, modify, and derive additional material.

As with adopting open-source software, there is often a reluctance to relinquish control. But if an open-source lab exercise “almost” meets the needs of a particular lesson, value can be extracted by deriving an exercise that “exactly” meets these needs, while complying with the open-source terms.

Conclusion

Developing effective power electronics lab exercises requires balancing cost, complexity, and degree of integration to maximize the absorption of concepts learned in lectures, while not frustrating the student or exceeding the teacher’s budget. This paper presented a range of experiments that can be executed using junk-box components, parts kit components and breadboards, and low-cost PCB modules. The freely available LTspice simulator provides a bridge between textbook formulas and the lab bench, allowing the student to validate textbook equations using nearly ideal components, as well as understand and model the imperfections of real-world circuits.

Experiments in analog and power electronics need to “keep up with the times”, incorporating modern, yet low-cost (or free) tools that students can quickly familiarize themselves with, such as USB-based oscilloscopes and free circuit simulators. Hands-on lab exercises continue to play a critical role in electrical engineering education; electronics is largely a world of invisible effects that can be intimidating to the novice, and the tangible experience of building and measuring circuits, early in a student’s academic career, can make the difference between the student pursuing further study in electrical engineering vs. other subjects.

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