Build to Win: A Hands-On Approach to Undergraduate Instruction in Power Electronics

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***Abstract* - We have developed an electronics prototyping kit and associated laboratory activities for undergraduate students. This kit enables personal, hands-on experimentation with practical power electronic circuits. We use the kit as the centerpiece of a design-based power electronics course because we are convinced that students cannot fully appreciate the design of power electronic circuits without hands-on activities. This approach is ideal for young engineers because a hands-on experience in a power electronics laboratory provides a broad, connected introduction to many engineering topics and ignites passion and excitement in students.**

I. BUILD TO WIN

Hands-on experimentation and design activities are increasingly important in our engineering education activities. It is no secret that the complexity and monolithic integration associated with modern commercial products have conspired to eliminate many of the practical, hands-on experiences that prepared past students for careers in science and engineering. At the same time, many of our classes have been refined to focus on the beauty and technique of analytical methods, perhaps increasingly without reference to the practical physical systems for which these methods were developed. To address these issues, we have developed hands-on undergraduate power electronics courses. Undergraduate power electronics courses are ideal opportunities to introduce engineering analysis and design [1]-[7].

The primary objective of our power electronics classes is to teach students to "build to win." On a broad level, these laboratories are intended to provide students with the confidence to design systems from scratch, the ability to understand the issues that underlie energy efficiency, and the skills to attack problems that cross disciplinary boundaries (e.g. thermal, electrical, and mechanical problems that must be solved in concert). Additionally, and perhaps most importantly, students also develop confidence in their ability to build, which in turn begins to cultivate a certain sense of intuition. At a specific level, typical expected outcomes for our students include the following:

- keep a clear laboratory notebook.
- read or draft a circuit schematic.
- construct electronic circuits using solder, printed circuit boards, and breadboards.
- read manufacturers' data sheets for components, e.g., magnetic materials like powdered iron cores.
- specify, design, and wind inductors and transformers.
- select and use a semiconductor power switch.
- design the inductor and capacitor in canonical cell converters.
- use logic chips to make a pulse width modulator.
- prevent shoot-through in a MOSFET totem-pole.
- drive a high-side MOSFET switch.
- create the drive waveforms for induction and permanent magnet motors.
- use and control dc motors.
- design, build, use and control a power electronic "buck" converter capable of processing over 1000 W.
- make practical products such as a stereo power amplifier, light dimmer, or flash strobe.
- use basic features of laboratory equipment like power supplies and oscilloscopes.

Power electronics is an exemplary early subject for young engineers because the design of successful power electronic circuits cannot be fully appreciated without building. To this end, we have developed a kit of prototyping electronics and associated laboratory activities for a one-semester class. This kit permits critically needed, personal, hands-on experimentation with practical power electronic circuits. Because this experimentation necessarily involves "real" loads that use power in interesting and relevant ways, we have found this class to be an exciting way to ignite students' passion for circuit design, physics, and modeling.

A totem-pole circuit consisting of two controllable MOSFET switches serves as the intellectual and physical cornerstone of the lab kit and its associated exercises. This relatively simple circuit can be used in many power electronic applications. For instance, a single totem pole is at the heart of each of the synchronously rectified canonical cell converters (e.g. buck, boost, buck-boost, etc.). Additionally, a single totem pole is found in other applications, including resonant-pole and Class-D type circuits typical of fluorescent lamp ballasts and stereo amplifiers. Using several totem poles, it is possible to build a poly-phase inverter and to experiment with motor drives. In the following sections, we first describe the physical prototyping hardware that we have developed, and we then present the practical applications that require students to use this hardware in the laboratory. All of the hardware and experiments can be scaled to meet any set of constraints, including class size, student experience, and semester length.

II. LABORATORY HARDWARE

We have designed special hardware that meets the challenges of teaching a hands-on power electronics course. This hardware provides a safe construction environment at a reasonable cost per student. It permits students to conduct flexible experimentation and enables the construction of circuits that can process thousands of watts under relatively "modern" conditions for power electronic circuits, i.e., with switching frequencies in the hundreds of kilohertz, current levels up to tens of amps, and voltage levels up to hundreds of volts.

A. Laboratory Kit

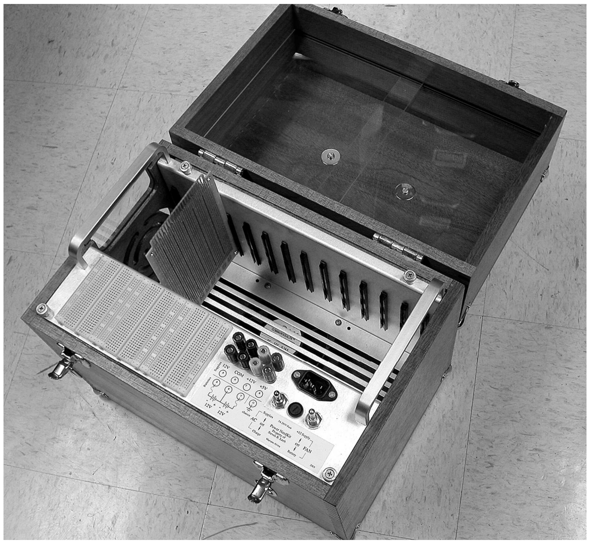

Figure 1: Power electronics laboratory kit.

A custom kit such as the one shown in Fig. 1 is provided on loan to each student participating in the class. The kit consists of a removable aluminum card rack that can be inserted into a wood case, making the system portable. The kit also holds a supply of tools, including a multimeter, oscilloscope probes, safety equipment such as goggles, and hand tools for circuit assembly. This kit supports the printed-circuit construction that is typically required for high performance power electronic circuits. The aluminum card rack, shown in Fig. 2, includes a line-powered triple output supply (e.g. +/- 12V and 5V). For added safety, each output is short-circuit protected. The aluminum card rack also includes a rechargeable battery compartment, making the kit fully "isolated" and portable, if desired. This portability has allowed us to construct laboratory activities that can be conducted free from a lab bench or a utility connection.

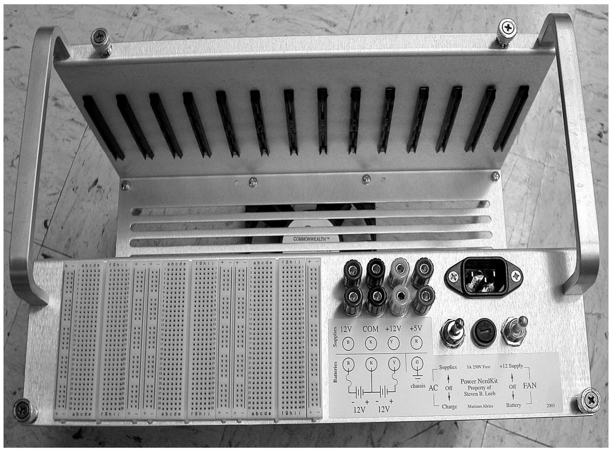

Figure 2: Removable card rack and power supplies.

B. Prototyping Cards

Students can use a suite of four different custom cards in their laboratory kit. These cards include: a breadboard card, a tri-totem card, a prototyping card, and a signal generator [1], [8]. The tri-totem and prototyping cards are generally "disposable" – students build, use, and keep or discard the cards after the laboratory. We order and purchase them in sufficient volume to keep the per-card cost relatively low, around four or five dollars each. The breadboard and signal generator cards are re-used each year.

Each of these cards slides into the removable card rack in the laboratory kit. Students mix and match cards as appropriate for a given assignment. All four cards have a common edge connector at the top. These connectors can be used to form a bus or "back plane" for a set of cards, permitting control and sensing signals to be exchanged between cards as needed. Typically, this finger edge connector and associated ribbon cable interconnect is not used for higher voltage and current signals. A set of screw terminals is available (as appropriate) on the edge of some of the cards for making connections that require higher current and voltage.

Three of these cards, the breadboard, prototyping, and signal generator cards, are shown in Fig. 3. Typically, students use the "breadboard" card to wire up relatively low current control electronics. For example, students might be challenged to make a ramp generator, PWM comparator, and other basic control elements on this card. Control signals can be passed over the ribbon connector to other cards. The prototyping card can be used for almost any purpose. A typical use is to hold larger filtering elements for higher power projects. The left half of this card provides a special array of larger diameter prototyping holes between the usual solder islands. These larger holes can be used to connect the heavier gage leads of high current components. They can also be used to help secure large components such as inductor cores, transformers, small fluorescent lamps and strobe tubes. The signal generator card can share the ribbon cable bus, and can be used to provide basic signals and some capability for modulation as well.

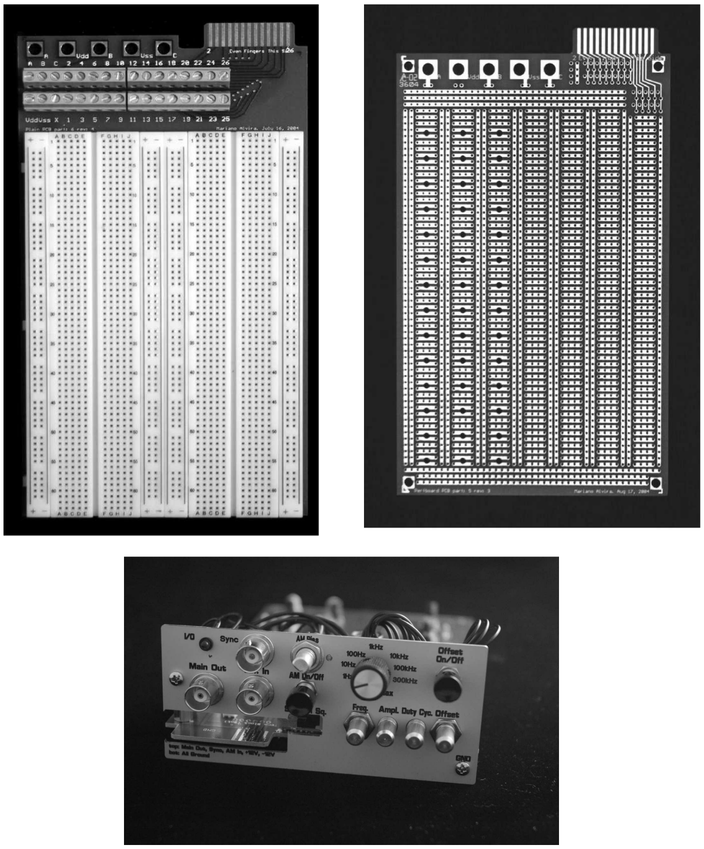

Figure 3: Clockwise from the top left: breadboard, prototyping, and signal generator cards. A 22-finger edge connector, e.g., at the top right of the breadboard card, permits easy control signal exchange between cards. Large solder pads for screw terminals are provided at the top left of the breadboard and prototyping cards for high current lines.

The tri-totem card, which is shown in Fig. 4, provides printed circuit wiring for three MOSFET totem poles connected between a common, possibly high-voltage rail (e.g., 200 to 400 V),. A partial schematic of the tri-totem board is shown in Fig. 5. Each of the three totem poles on the tri-totem card offers pre-wired printed circuit traces that are populated by the students. Student in the class are permitted to solder and use the card only after they have learned about the MOSFET and the floating capacitor driver scheme facilitated by the IR2125 gate driver chip [7]. We give students the tri-totem card for the first time during a "solder clinic" conducted by the teaching staff. Because the students will have already built a low power version on the breadboard, this approach ensures that students understand the circuit, allowing us to shift the focus to layout and construction.

Students can wire as little or as much of each totem stage as is needed for a particular project. They typically use four or five tri-totem cards during the course of a term. It is easy to use either two active switches for a totem or to replace one of the switches with a passive diode. So, for example, students can experiment with synchronous rectification, or deploy a MOSFET and freewheeling diode combination for a more traditional canonical cell. The IR2125 drivers receive gate drive signals from student-designed circuits. Signals for the IR2125 control pins may be provided over the tri-totem edge connector or by circuitry constructed in the prototyping area at the bottom of the tri-totem card.

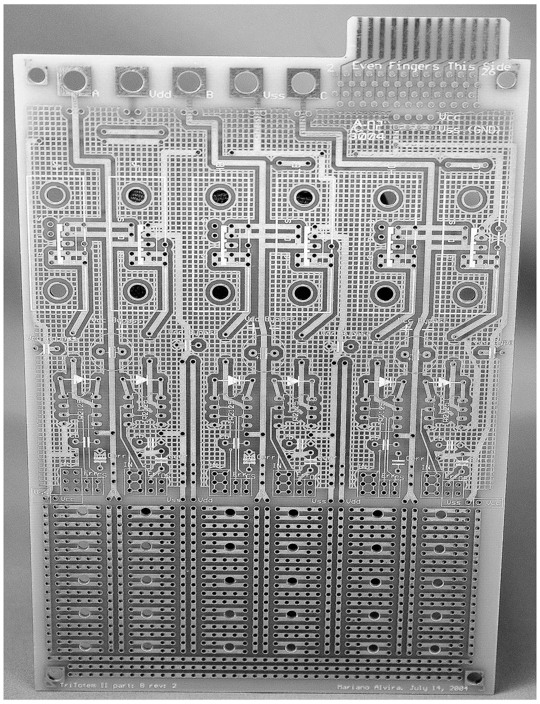

Figure 4: A "bare" tri-totem card.

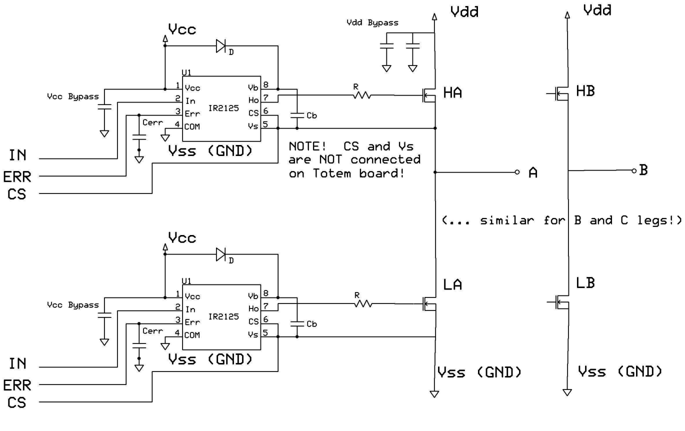

Figure 5: Partial tri-totem schematic.

Figure 6 shows a fully populated tri-totem card constructed by a student. The screw terminals permit connection with crimp lugs for the totem power rails (Vdd, Vss) and for the totem midpoints (A,B,C). Control signals in this case are provided over the card edge connector.

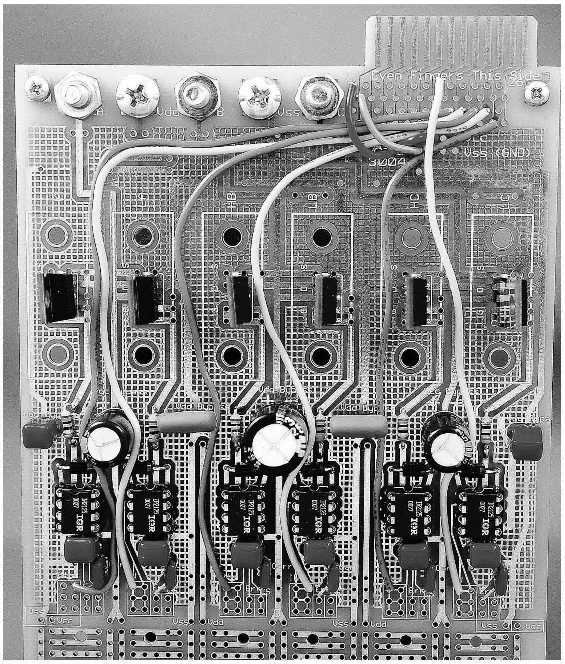

Figure 6: Fully populated tri-totem card.

C. *Lab Stations*

We have constructed a variety of different laboratory stations to permit students to observe, model, and control real plants with industrial and commercial relevance. For example, Fig. 7 shows a "LoadBoy" load station introduced early in the term and used throughout. This load station provides a pair of brushed dc machines that can be separated or easily shaft connected for motor-generator experiments. The load station also provides a pair of mid-range speakers for audio-generation experiments, a pair of incandescent light bulbs, and a patch of breadboard and a knife switch for quick interconnection and alteration of load arrangement. All of these loads would typically be explored during the first two-week lab assignment.

We have constructed lab stations that can receive the aluminum card rack, permitting students to first test their circuits in the rack on a bench, and then move the rack to control "real" systems like larger motors, flashtubes, and induction heating coils. For example, we have constructed a fleet of go-carts shared across our universities for use in the classes. One of the go-carts is shown in Fig. 8.

Each go-cart contains an on-board 36-volt, 17-amp-hour battery pack (under the seat). A 1.5 horsepower dc motor drives a rear-wheel on the tri-cycle-configured cart. Over the rear wheel, each go-cart provides a plastic tool box and rack-mount system that is compatible with the power electronics lab kit. When students in the class have completed their designs, they can remove their aluminum card racks from their kits for a "drop in" fit into the tool box on the back of the go-cart, as shown in Fig. 9.

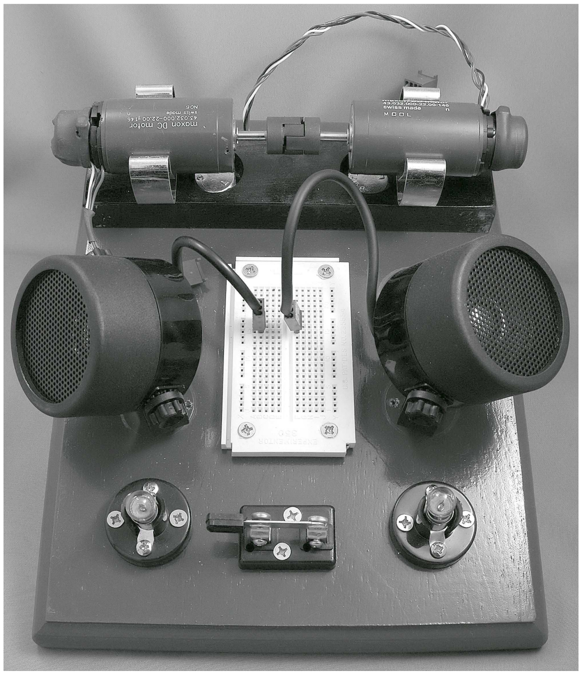

Figure 7: LoadBoy.

III. LABORATORY ASSIGNMENTS

The precise course content of the power electronics laboratory can vary to support different curriculum needs. An "aggressive" one-semester offering, which we have successfully conducted for the past three years, challenges students with four separate two-week laboratory exercises, followed by a quiz and a four-week final project. The final project is an independent project defined and conducted by each student with the supervision of the teaching staff.

A. *Sample Laboratory Exercises - Laboratory 1*

The first laboratory challenges students to review basic circuit theory in the context of circuits and problems relevant to power electronics. They use resistors, diodes, and zener diodes to construct voltage references and to review thevenin equivalents in order to compare the terminal behavior of these references. They construct linear regulators using transistors and op-amps. They review the construction of oscillators and the use of comparators, logic gates, and RC circuits to create pulse-width modulators that provide shoot-through protection. They learn about the use and application of gate-drive circuits,

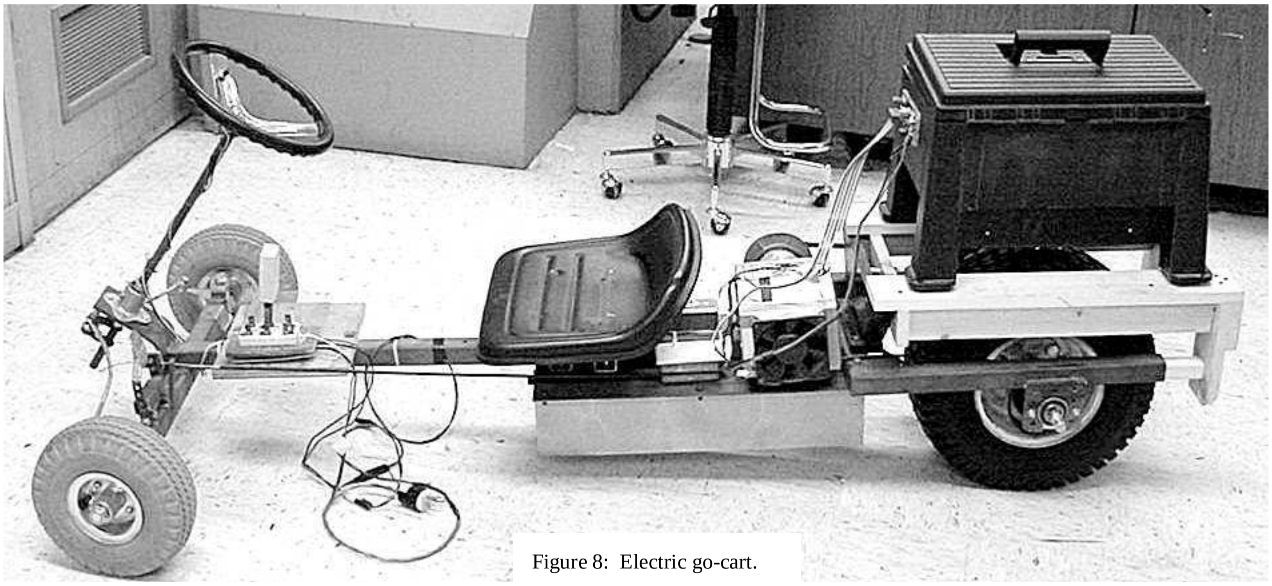

Figure 8: Electric go-cart.

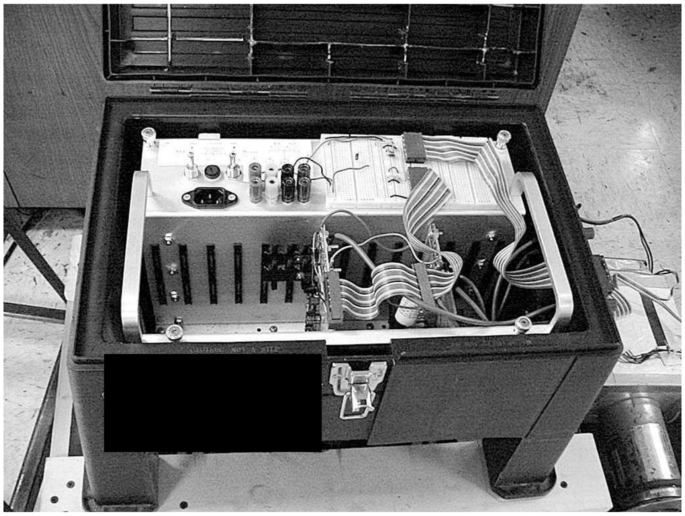

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Figure 9: Card rack mounted in go-cart.

including the IR2125 floating driver. To drive a speaker, students construct both a linear and a switching audio amplifier. They use this application to compare the efficiencies of the two approaches to power conversion. Voltage, current, and power levels are relatively low during this first lab (10's of watts), and the construction effort occurs primarily on the breadboard card. This gives the students time to "warm up" before working with the more expensive solder cards, which can be more difficult for an unprepared student to repair, modify, and correct in the face of bad design choices. The first laboratory culminates with the design and construction of a 15W Class-D audio switching amplifier. A typical student-designed schematic is shown in Fig. 10. The circuit includes a PWM generator that consists of several key functional blocks.

In all of our laboratory exercises, students choose components to create needed functional blocks. In the example shown in Fig. 10, the 555-timer provides a rough triangle wave for the PWM comparator. Other choices are possible – students also use the 74HC14 hysteretic comparator to make rough triangle waves, for example, using RC feedback around a comparator gate. The PWM comparator is typically implemented with an LM311, which compares the triangle wave with a level constructed from a dc offset and a capacitively coupled audio input. The PWM output of the LM311 is passed through a shoot-through protection block constructed of NAND, NOR, and inverter gates. The resulting high and low-side signals serve as control inputs for the two IR2125 drivers controlling the MOSFETs in a switching totem pole. This totem pole drives a speaker. When the circuit is properly designed, the students hear only the modulating signal, giving them an auditory demonstration of averaging. They are also encouraged to explore the effects of "undersampling" by varying the triangle wave frequency created by the 555 (i.e., the switch frequency) with respect to the frequency content of the audio signal. They can experiment with pure tones from a signal generator and also with audio signals from any convenient source in the lab, (e.g., CD player, radio, iPod, etc.).

B. Sample Laboratory Exercises - Laboratory 2

For the second laboratory, students begin to use the tri-totem and prototyping solder cards to construct circuits capable of processing higher power levels. As an example, the first exercise in the second lab is to construct a step-down converter to drive the dc motor in the electric go-cart. Varying the duty cycle of this circuit provides a throttle control. The design of this go-cart drive circuit can be used as a lecture demonstration, as a lab exercise, or both. This activity provides an opportunity to introduce the brushed dc motor, and it also provides a motivational beginning for the discussion of canonical cell converters. A model for the complete power stage of the drive is shown in Fig. 11. Note that in that figure, the source labeled "M" represents the back-EMF of the dc machine and the 1.2 Ohm resistor represents the motor armature resistance.

We challenge the students to understand and use measured information from the go-cart. In this lab, they begin to understand and use component specification sheets for MOSFETs, magnetic components like powdered iron toroids, and capacitors in order to design the go-cart drive. When they have completed a first-cut design, but before they begin assembly, we meet with each student for a one-on-one, hour-long design review. During the design review, the students make an oral presentation in which they explain their component selections and circuit design. Students are required to present their calculations and to provide supporting rationale for all of their decisions.

From measurements and discussions in lecture, the students will know some basic facts about the go-cart. These include:

- The go-cart battery pack nominally provides 36 V.
- When the battery pack is connected to the go-cart dc motor through a knife switch, the motor draws 30 A when the cart is stalled.
- During steady-state driving on level ground, the motor draws 15 A and the motor shaft (which is connected to the wheel through a gear ratio) turns at 1300 RPM.
- The motor has a nominal armature resistance of 1.2Ω.

Using this data and some additional specifications provided in the lab handout, a student design might proceed as follows.

Typically, students begin by selecting a switch frequency, $f_{sw.}$ The switching frequency is constrained by a number of factors. At this point in the course, the students have learned that the "stock" IR2125 driver will have a lower frequency limit around 400 Hz. They have also learned the value of keeping the switch frequency above the audio range, e.g., greater than 20 kHz, if possible. These two considerations establish lower bounds on the drive frequency.

Students determine an upper bound on the drive frequency by examining the available MOSFET switches stocked in our laboratory. The most capable MOSFET we typically stock that would be appropriate for the go-cart voltage and current levels is the IRF1407, a 75-volt part with a nominal on-state resistance of 7.8mΩ. In lecture, we review the loss mechanisms that heat the MOSFET during operation, including conduction and switching losses. The IRF1407 has an absolute maximum junction temperature rating of 175 degrees C. Our lab stocks heat sinks rated for a 10 degree C per watt rise. Accounting for thermal drops between the junction and heat sink, students typically conclude that the MOSFET can be allowed to experience an absolute maximum total dissipation of 13W, resulting in a heat sink temperature of 130° C above ambient, leaving the MOSFET perilously close to its absolute maximum junction temperature. Students generally understand that this is an extreme maximum, not to be approached casually, but reasonable as an absolute design bound.

The worst-case scenario for the high-side MOSFET labeled HB in Fig. 11 occurs when the down converter is switching near a duty cycle of unity while the go-cart is completely stalled. That is, nearly full throttle with the go-cart rammed against a wall or other obstruction. In this case, the MOSFET will dissipate conduction losses commensurate with approximately 30A of load current. At high temperatures, the MOSFET on-state resistance is de-rated, and will be closer to 10mΩ or more. This leads students to conclude that at least 9 W will be dissipated due to conduction losses. With a 13W "loss budget" for the MOSFET, this leaves at most 4W to accommodate the switching losses.

A certain amount of energy E_{diss_on} is dissipated in the MOSFET during turn-on. An amount E_{diss_off} is dissipated during turn-off. The IR2125 provides assymetrical on and off gate currents. Students may take a conservative approach and approximate the IR2125 behavior by its lower drive current of one amp. In this case, the energy dissipated during either turn-off or turn-on is simply E_{diss}, which can be estimated from the MOSFET datasheet using the sum of reasonable values for the gate-to-source and gate-to-drain charge. A reasonable absolute maximum of about 130nC is typically assumed. With the one-amp gate drive current provided by the IR2125, a peak drain current of 30A, and a peak drain voltage of 36V, students find that E_{diss} is approximately 70μJ. With the knowledge that the maximum permissible dissipation due to switching losses is 4W, students can then solve for an upper bound on the maximum allowable switching frequency:

$$f_{sw\_max} = P_{sw}/(E_{diss\_on} + E_{diss\_off}) = 4/140\text{e-}6 = 29 \text{ kHz}.$$

Using this switch frequency, the students then design the converter's output filter so that it minimizes the switching-frequency component of the motor's terminal voltage. In lecture, we explain the need to limit high frequency current ripple in the motor to avoid damage to the motor insulation system. Students select appropriate capacitors that can tolerate the high-frequency ripple currents, and select a core and wire gage for a filter inductor to meet the required design specifications.

Students bring all of these design calculations and their supporting rationale to the design review meeting. At this meeting, the instructors work with the students to correct conceptual errors, find computational mistakes, and to review the reasonableness of assumptions made during the design process, e.g., MOSFET conduction resistance at high temperature operation. Following a successful design review, students have permission to attend a solder clinic and to obtain the parts needed to build their full go-cart drive. This drive includes both the down converter and a PWM generator not unlike the one shown in Fig. 10. In this case, however, the

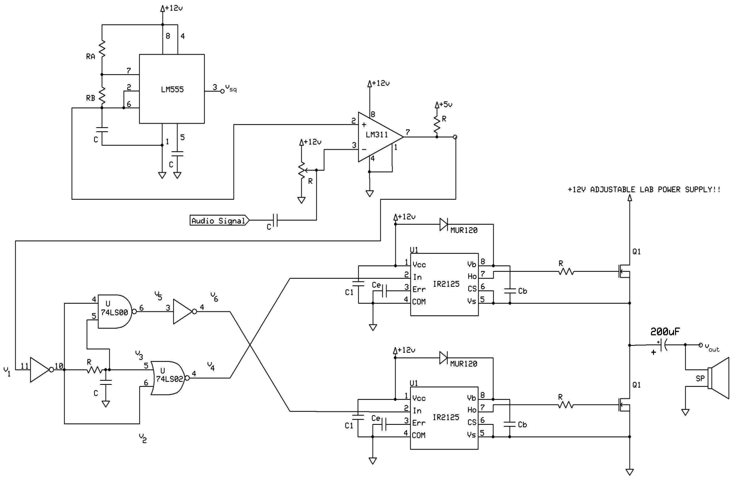

Figure 10: Student-built audio amplifier.

LM311 inverting input is connected to a potentiometer on the steering wheel of the go-cart, which serves as a throttle control. For safety reasons, the final “check off” of this hardware is conducted under the supervision of the staff during an exciting day in the lab area. A typical check off is shown in Fig. 12.

IV. DISCUSSION

We have developed a suite of additional exercises similar to the two discussed here. During the course of a full semester, students will progress through a sequence of design and build challenges that will introduce them to real-world examples of dc-dc, ac-ac, dc-ac, and ac-dc conversion. These design and build activities include the construction of a resonant fluorescent lamp ballast, an incandescent lamp dimmer, a flyback regulator for a high voltage flash strobe, a boost converter for making a portable stereo amplifier with a battery-source input, and a three-phase inverter for operating AC rotating machines. Key design and build activities in each lab are organized around the “design review followed by check off” plan described for the go-cart activity. When the students complete the assigned labs, they are given the opportunity to define and execute a final project of their own design.

The strong connection between power electronics and “real,” industrial and commercially relevant systems has proven to be a valuable motivator for engineering students. Physics and circuit design become tangible when connected together in a hands-on power electronics laboratory. We suspect that this design and build approach with power electronics may be useful in many more places in our engineering curriculum; for example, in introductory circuits classes, courses in feedback control, and embedded programming classes.

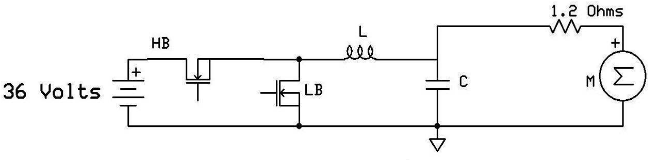

Figure 11: Down converter and go-cart motor.

Figure 12: A winning student check off.

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