Build to Win: Power Electronics

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***Abstract*—We have developed a hands-on kit for prototyping power electronics. This kit permits students to design and build power circuits capable of processing thousands of watts safely, while preserving design flexibility, i.e., avoiding "cookbook" laboratory assignments. This system exposes students to real-world operating conditions and parasitics that often define and delimit a power electronic design in industry. This hardware and the associated approach to instruction provides flexible, repeated design-and-build experiences in a single-term undergraduate class typically taken by juniors and seniors.**

***Index Terms*—Drives, electromagnetic actuators, engineering education, motors, power electronics, power system components.**

I. BUILD TO WIN

A "perfect storm" of three technical opportunities in power distribution is encroaching. First, power electronic circuits are becoming increasingly affordable and widely deployed to provide unique control and energy processing capabilities in consumer and industrial loads and on the power system grid itself. Second, ever increasing attention, including regulatory attention, is being paid to the energy consumed by electronic and electromechanical loads on the grid, and waste associated with these and related loads. Third, distributed sources are supplying the power grid in increasing quantity. Practical instruction in power electronics is a necessity for engineers working with energy.

Safety and cost considerations often encourage introductory power electronics classes to focus on simulation, lower voltage scale circuits, and computer tools for preliminary experimentation [1]–[3]. However, power electronics is an exemplary early subject for young engineers because the design of successful power electronic circuits cannot be fully appreciated without building. For power electronic circuits, physical layout as well as the abstract power electronic circuit schematic are critical in determining and achieving electrical design intent [4]. While "basic concepts can be illustrated at fairly low power" [5] challenges and problems often appear only at realistic voltage, current, and power levels in hardware with parasitic components. A 1 kW down converter for an electric cart drive will expose design challenges quite distinct from a 10 W dc-dc converter with a similar schematic or block diagram.

The power electronics community has been creatively responsive to the need for pedagogical hardware experience over the past three decades [5]–[9]. In particular, the educational leadership exemplified by [10]–[13] has revitalized power electronics instruction in many engineering programs, including ours. As with the construction of radio frequency or wireless circuits, understanding parasitic components and layout are as much a part of a successful power electronic circuit design as consideration of circuit topology. We have developed a hands-on kit of prototyping electronics and associated laboratory activities for a one-semester class to expand the range of design options and "parasitic" challenges offered to students.

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. We are using this kit to offer collaborative power electronics laboratory courses for undergraduate students at our respective universities. The hardware and experiments are scalable for larger or smaller groups of students, for different lengths of a course or part of a course, and can be rearranged as needed to emphasize different topics. This paper describes the kit and example laboratory exercises used to offer these classes.

The objective of these classes is to teach students to "build to win." Students who complete this type of power electronics laboratory have confidence to design systems from scratch, to attack problems that cross discipline boundaries, and to appreciate the challenges of efficient energy processing. They develop confidence in their ability to build, and enjoy design challenges that might involve friendly competition, e.g., achieving maximum range from an electric go-cart.

A totem pole of two controllable MOSFET switches serves as the intellectual and physical cornerstone of the lab kit and exercises. The ubiquity of the totem-pole as a building block in power electronic systems [10] has motivated the design of a flexible kit built around the reliable construction of totem pole circuits to safely provide design experiences for students at higher voltage and current levels than typically found in undergraduate teaching laboratories. With the totem pole, it is possible to build all of the canonical cell converters (buck, boost, buck-boost, etc.) as well as other useful circuits, including resonant pole and Class-D circuits that typify fluorescent lamp ballasts and stereo amplifiers. With several totem poles, it is

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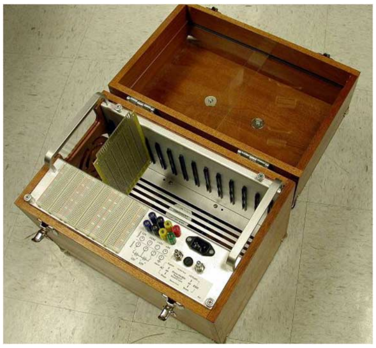

Fig. 1. Power electronics laboratory kit.

possible to build a poly-phase inverter and to experiment with motor drives.

II. LABORATORY HARDWARE

We have designed special hardware that meets the challenges of teaching a hands-on power electronics course [14]–[16]. 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 "modern" conditions for power electronic circuits, i.e., with switching frequencies in the hundreds of kilohertz, current levels in the tens of amps, and voltage levels in the hundreds of volts, if and as needed for any particular project.

A. Laboratory Kit

Every student participating in the class is loaned a custom kit, as shown in Fig. 1, for constructing power electronic circuits and systems. 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 including safety 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 includes utility-line powered supplies that provide short-circuit protected voltage rails for ±12 volts and 5 volts. The aluminum card rack can be earth grounded and 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, as will be discussed shortly.

B. Prototyping Cards

Students can choose from a suite of four different custom cards for use in the laboratory kit. These cards include: a breadboard card, a tri-totem card, a prototyping card, and a signal generator [14]–[16]. 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 a card. The breadboard and signal generator cards are re-used each year.

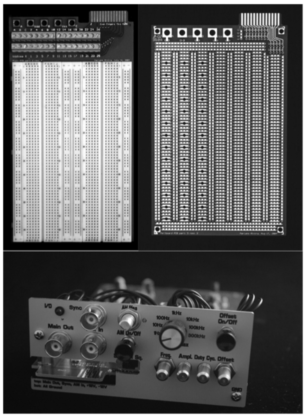

Fig. 2. Clockwise from the top left: breadboard, prototyping, and signal generator cards. A 22-finger edge connector, e.g., at the top right of the breadboard card, permits easy control signal exchange between cards.

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. This begins the engagement of the "cub" designer in thinking about EMI considerations as signals and power are shared across the cards. All four cards have a common edge connector at the top of the card. This connector can be interconnected to form a bus or "back plane" for a set of cards, permitting control or sensing signals to be exchanged from card to card. Typically, this finger edge connector with ribbon cable interconnect would not be used for higher voltage and current signals. A set of screw terminals is available for higher current and voltage connections between boards.

Three of these cards are shown in Fig. 2: the breadboard, prototyping, and signal generator cards. 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, and is typically used, for example, 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 for tie-wraps or other securing means for larger filtering components, transformers, small fluorescent lamps or strobe tubes, etc. 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.

A "tri-totem" card provides printed circuit wiring for three MOSFET totem poles connected between a common, possibly high (e.g., 200 to 400 volts), voltage rail. A partial schematic of the tri-totem board is shown in Fig. 3. 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 [17]. We give students the tri-totem card for the first time during a "solder clinic" conducted by the teaching staff. This approach ensures that students

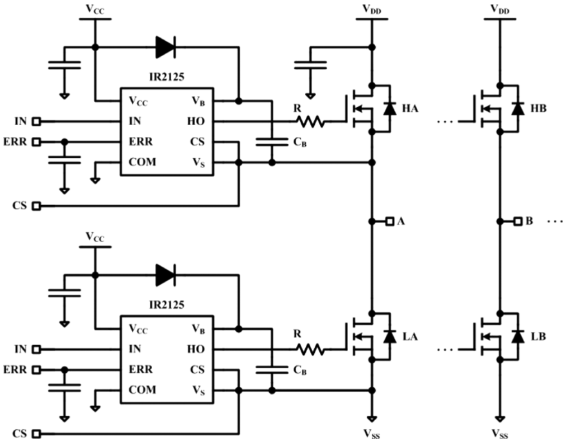

Fig. 3. Partial tri-totem schematic.

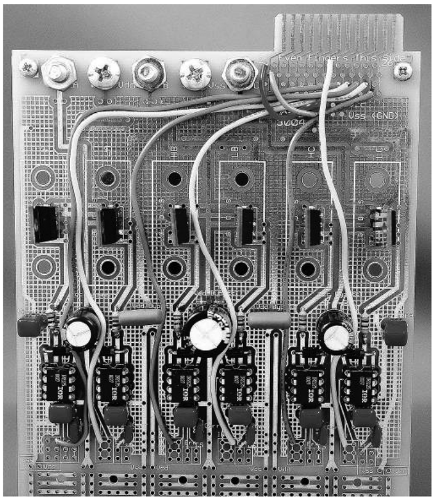

Fig. 4. Fully populated tri-totem card.

understand the circuit (they will have already constructed a low power version on a breadboard in a previous lab) and can construct it responsibly and reliably.

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.

Fig. 4 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.

C. Lab Stations

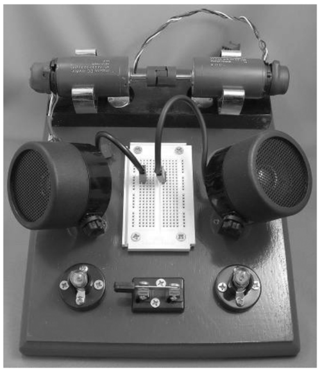

Fig. 5. LoadBoy.

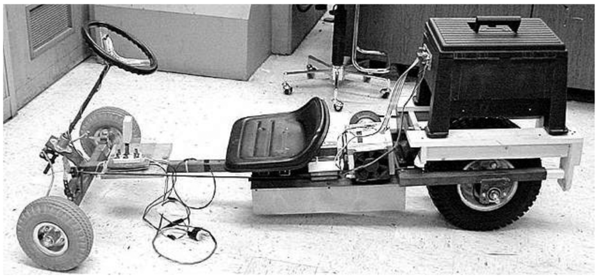

Fig. 6. Electric go-cart.

Different laboratory stations to permit students to observe, model, and control real plants with industrial and commercial relevance. Fig. 5 shows a “LoadBoy” load station introduced early in the term and used throughout the course. 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.

We have constructed lab stations that can receive the aluminum card rack, including a fleet of electric go-carts. These stations permit 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. This two-step, mobile approach is essential for ensuring safety, permitting initial testing in a controlled but expandable environment. Fig. 6 shows an example go-cart. Each go-cart contains an on-board 36-volt, 17-amp-hour battery back (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 go-cart, as shown in Fig. 7.

III. LABORATORY ASSIGNMENTS

The precise course content of the power electronics laboratory can vary to support different curriculum needs. An “aggressive” one-semester offering that 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

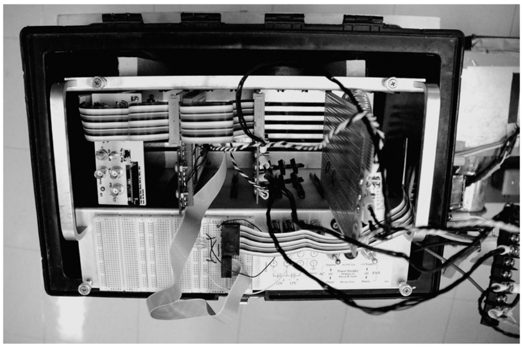

Fig. 7. Card rack mounted in go-cart.

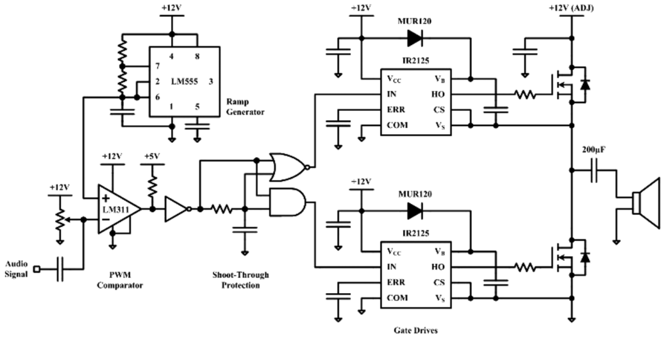

Fig. 8. Student-build stereo amplifier.

project defined and conducted by each student with the supervision of the teaching staff. Key lab activities are described below:

A. Audio Amplifier

The first laboratory challenges students to review basic circuit theory in the context of circuits and problems relevant to power electronic circuits. 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 modulation (PWM) control circuits that provide shoot-through protection circuitry. They learn about the use and application of gate-drive circuits, including the IR2125 floating driver. They compare the efficiency of a linear driver for an audio speaker versus a switching amplifier for the same speaker. 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 15 watt Class-D audio switching amplifier. A typical student-designed schematic is shown in Fig. 8. The circuit includes a PWM generator that consists of several key blocks.

Students choose components to create needed functional blocks. In the example shown in Fig. 8, 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, giving the students the opportunity to experience an auditory demonstration of averaging. They hear the modulating signal, and not the switch frequency, when the circuit is properly designed. They can also 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. Go-Cart Drive

Beginning with the second laboratory, students design complete systems essentially "from scratch. " Here in this section, we therefore focus in some detail on the calculations a student might do to solve this design challenge, the construction of an electric drive for a 1000 W go-cart motor. Students begin to use the tri-totem and prototyping solder cards to construct converter circuits capable of processing higher power levels. Varying the duty cycle of this converter gives a throttle control for the go-cart. 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 and study the brushed DC motor in lecture, and also to begin to explore canonical cell converters.

We challenge the students to understand and use measured information from the go-cart. In this lab, they also 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 of their component selections and circuit design for a down converter driving a go-cart motor, as shown modeled in Fig. 9, along with their calculations and supporting rationale summarized in a lab notebook. The source labeled "Back EMF" in Fig. 9 represents the back-EMF of the DC machine, and the 1.2 Ohms represents the motor armature resistance.

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 volts.
- When the battery pack is connected to the go-cart DC motor through a knife switch, the motor draws 30 amps when the cart is stalled.
- During steady-state driving on level ground, the motor draws 15 amps 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 1.2 Ohms.

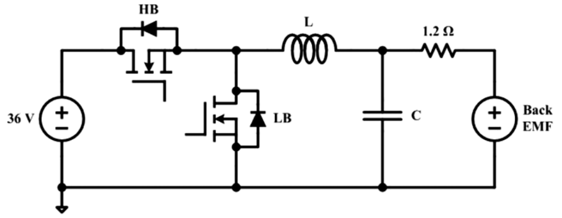

Fig. 9. Down converter and go-cart motor.

Using this data and some additional specifications and information provided in the lab handout as a starting point, a student design might proceed with the following logic:

Typically, students will begin by selecting a switch frequency, $\mathrm{F_{sw}}$. 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 audio frequencies, 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 7.8 milliOhms at room temperature. 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 6-degree C-per-watt temperature 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 22 watts, resulting in a heat sink temperature of 130 degrees 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. 9 occurs when the down-converter is switching near a duty cycle of unity while the go-cart is completely stalled, e.g., when the driver applies 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 30 amps of load current. At high temperatures, the MOSFET on-state resistance is de-rated, and will be closer to 20 milliOhms. This leads students to conclude that at least 18 watts will be dissipated in conduction losses. With a 22 watt "loss budget" for the MOSFET, this leaves at most 4 watts to accommodate the switching losses.

A certain amount of energy $\mathrm{E_{diss\_on}}$ is dissipated in the MOSFET during turn-on. An amount $\mathrm{E_{diss\_off}}$ is dissipated during turn-off. The IR2125 provides asymmetrical 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 $\mathrm{E_{diss}}$, 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 total absolute maximum of about 130 nC. With a one-amp gate drive current, peak drain current of 30 amps, and a peak drain voltage of 36 volts, students find that $\mathrm{E_{diss}}$ is approximately 70e-6 Joules. With the knowledge that the maximum permissible dissipation due to switching losses is 4 watts, students solve for an upper bound on the maximum allowable switching frequency:

$$\mathrm{F_{sw\_max}} = \frac{\mathrm{P_{sw}}}{(\mathrm{E_{diss\_on}} + \mathrm{E_{diss\_off}})} = \frac{4}{140\mathrm{e}-6} = 29\ \mathrm{kHz} \tag{1}$$

or about 30 kHz in round numbers. At this switch frequency, the students then proceed to design the down-converter output filter inductor and capacitor values to achieve a mandated specification on switch frequency ripple voltage applied to the motor. 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.

Fig. 10. Winning student check off.

Students would bring all of these design calculations and their rationale to the design review meeting. At this meeting, the instructors will 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 use the solder cards and other parts to build their full go-cart drive, which includes both the down-converter and a PWM generator not unlike the one shown in Fig. 8. Now, however, the 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 student check off is illustrated in Fig. 10.

C. Flash Strobe

Beginning with the third laboratory exercise, students confront problems that require relatively high voltage. Safety, as always, is the highest priority for all class activities. The totem card system permits testing and flexible debugging at lower voltage levels, while also providing the capability to operate at higher voltage levels as a student's work is proven.

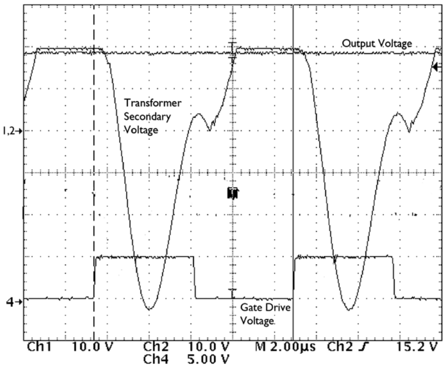

Fig. 11. Flyback waveforms.

For example, in the third laboratory, we challenge the students to build a flash strobe for photography applications using a xenon flash tube. The SCR-triggered flash tube circuit typically requires an input voltage of about 200 V. Students design a high-voltage converter, e.g., a flyback, to convert the 3 to 12 volts available from a portable battery to the hundreds of volts needed for the flash tube and associated trigger coil input. The totem card is perfect for this application, even though the flyback converter does not need two active MOSFETs. The transformer primary can occupy the "high side" connection on the totem card, and the lower MOSFET is used to switch the transformer primary. This activity engages students in designing an high frequency transformer and an appropriate clamp circuit for the leakage inductance.

In designing power electronics, there is no substitute for real world experience, and the students learn this first hand in this laboratory. The flyback design requires a trade-off between nominal control duty cycle and transformer turns ratio. Many students will attempt to optimize their design for low switch stress, economical semiconductor selection, and, therefore, a duty cycle of 0.5. This choice places the burden of high voltage generation on the transformer turns ratio as opposed to exploiting the converter's duty-cycle controlled capability to boost voltage. The transformer is required to satisfy several circuit demands, including minimal leakage inductance, sufficient magnetizing inductance to meet current ripple and continuous-conduction mode specifications, and, of course, to provide an adequate turns-ratio for creating high voltage. Students taking this approach typically wind up with a transformer with a significant, e.g., 1-to-8, turns-ratio, and a fairly large number of primary turns, e.g., 100 turns, on cores available in the laboratory. They are then often surprised to discover the results illustrated in Fig. 11, captured during a low-voltage input student test in our teaching laboratory.

Fig. 11 shows three waveforms from a student-built flyback converter: output voltage on the top trace, transformer secondary voltage on the middle trace, and primary side gate-drive voltage on the bottom trace. With an "ideal" transformer, students would expect the transformer secondary voltage to look like a square wave. In this case, it does not. When the switch is off (bottom trace is low), the secondary voltage is essentially pinned equal to the output voltage (plus a diode drop) while the flyback action transfers magnetizing current to the output, all essentially as expected. However, when the primary side switch is on, the high-Q resonant circuit, formed by the transformer inductances and the secondary side parasitic winding capacitance, rings. Students are often surprised to discover that this parasitic energy storage, the winding capacitance, really exists and actually effects their design. At this point, they can begin to refine their design, considering whether to use and design with this effect, or modify the flyback operating characteristics, especially duty cycle, to require less asymmetry between the transformer primary and secondary windings and a lower absolute number of turns. Notice that the experiment in Fig. 11 is conducted entirely at under-50-volt levels while a student works with instruction staff to experience and learn first-hand about parasitic effects in power electronic circuits. With a proper appreciation, students can then move on to complete a design that requires 200 volt operation to provide the intended energy conversion solution for the flash tube.

D. *Motor Control*

We have also developed a flexible, multi-use, 3-phase axial-flux machine suitable for laboratory instruction [18]. This machine permits design challenges, pedagogical opportunities, and possibilities for friendly student competitions. This machine is configurable as a permanent magnet (brushless dc) motor or as an induction machine. It would typically be used with a three-phase inverter shown in Fig. 5. In some cases, e.g., an embedded control laboratory, we might provide part of the inverter, such as the three-MOSFET totem poles and gate drivers, while the students would provide the drive logic and control signals.

A desire for quick re-configurability led us to an axial-flux design. For example, one of the desired experimental setups for the induction machine involved the possibility of varying the thickness of the rotor conductor and also the machine air gap. With an axial-flux design, these quantities can be changed quickly by substituting rotor disks and altering the axial position of the rotors. The sides of the motor provide space to mount other electromechanical devices for interacting with the machine. For example, an encoder and a prime mover (a dc motor) can be added to the machine, permitting use as a controlled drive or as a generator. The rotors are double-sided, with a copper disk (for an induction machine) on one side and magnets (for a permanent magnet machine) on the other side. There is substantial space in the frame for additional expansion, e.g., a multi-rotor machine. Spacers can be inserted between the rotor disks and the Gramme-ring stator in order to control the air-gap dimension.

Fig. 12 shows the ac machine in use in the laboratory. The Gramme ring in the center of the motor box is secured to the base of the motor. The steel disks are mechanically keyed to the shaft, which can turn freely on the bearings mounted in the box walls on the left and right sides of the picture. The machine is shown configured as an induction machine, with copper disks secured to the steel rotor backing. The steel disks can also be "flipped" to bring magnets and a steel magnetic circuit facing the Gramme-ring stator. Students may use the dc motor shown on the far right of Fig. 12 to measure machine torque. We also give them a torque bar and spring scale in the laboratory to measure the static torque produced by the machine.

There are innumerable experiments that can be performed with the induction and PM machines that can be constructed using the experimental ac machine. We have challenged students to characterize the induction machine, for example, and

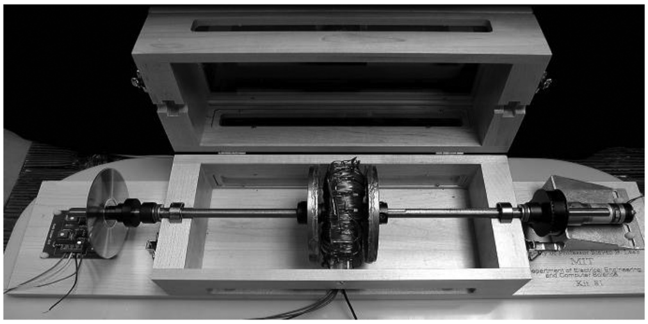

Fig. 12. Experimental ac machine in the laboratory. A brushed dc prime mover can be connected on the right. A position encoder constructed by the students is shown on the left.

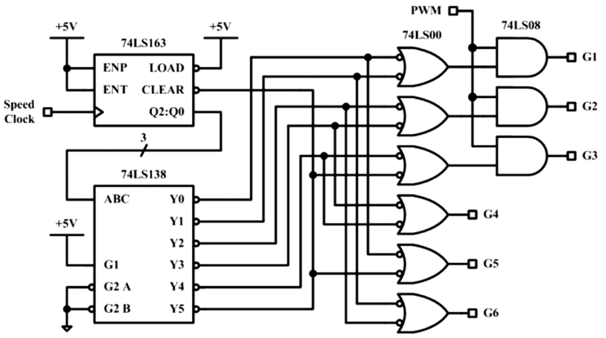

Fig. 13. Finite state machine controller.

to develop analytical and experimental torque-speed curves. We have posed lab experiments where we ask the students to lock the machine rotor and drive the machine with a variable-frequency, three-phase ac power supply. They measure the phase currents and line-to-neutral voltages applied to the machine in order to characterize a circuit model for the motor.

We have also challenged students to construct drives for the machine and operate it as either a PM or induction motor. A typical student-built, finite-state machine-based drive circuit for the motor is shown in Fig. 13. In the case of the induction machine, the "speed clock" signal comes from a signal generator that effectively sets the synchronous speed. For the brushless pm configuration, the speed clock signal comes from the encoder on the ac machine. This effectively slaves the count of the finite state machine to the rotor position, creating a solid-state commutator for the motor. The counter (74LS163) and selector (74LS138) provide signals that are combined by appropriate logic circuitry to create a desired drive pattern. The 74LS00 NAND gates create a 120 degree conduction pattern in the circuit shown in Fig. 13. The 74LS08 AND gates add a PWM modulation to each phase voltage, thus providing amplitude control of the waveforms in addition to the frequency control offered by the speed clock signal. The output lines labeled G1, G2, and G3 drive the inputs drivers for the top three switches in a three-phase totem pole. The lines connected to the G4, G5, and G6 signals drive the complementary bottom switch in each totem leg, respectively.

Each of the six MOSFETs in a three-phase inverter board built by the students is controlled or driven by an IR2125 gate driver from International Rectifier. The input lines for these gate drivers are provided by the G1 through G6 lines of the finite state machine shown in Fig. 13. Most recently, we have begun to use digital engines like the Cypress Semiconductor PSoC (programmable system on chip) [19] to provide digital drive for the inverter.

IV. ASSESSMENT

We have developed a suite of many 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. 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.

Assessment of student learning is conducted as an active process throughout the term, in concert with the students, to continuously improve and tailor the individual learning experience. Prior to having students build in the lab, we conduct one-on-one design reviews with each student during each lab with a graded presentation and discussion of design plans involving oral and written components. These activities lead students to the "ultimate" assessment: the successful demonstration of working hardware systems to the teaching staff at a half-dozen assessment points in the laboratory over a semester. For a typical class size of 36–40 students, this laboratory course experience has been one of the best received offerings in the department and associated school of engineering, with overall course ratings of 6.8 (out of a "best rating" of 7) in both the 2012 and 2011 offerings.

While the exercises outlined in this paper are most often targeted at juniors and seniors in our schools of engineering, we have had wonderful experiences extending modified versions of these activities to K-12 and post-graduate audiences. The entire go-cart/down converter activity, for example, can be reduced to a more portable activity, with easier, lower current safety challenges while still using our totem card system, by working with a small mobile robot appropriate in high school classes. We have that practical excitement and empowerment can be offered to students by sneaking these activities into other classes, e.g., a microcontroller laboratory or a field theory class, that can use power electronics problems as motivating examples.

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REFERENCES

[1] I. Batarseh and D. A. Kemnitz, "Undergraduate education in power electronics," in *Southcon/94 Conf. Record 1994*, pp. 207–213.

[2] E. A. McShane, M. Trivedi, and K. Shenai, "An improved approach to application-specific power electronics education," *IEEE Trans. Educ.*, vol. 44, no. 3, pp. 282–288, Aug. 2001.

[3] Z. Jakopovic, Z. Bencic, and V. Sunde, "Computer in power electronics education," in *Proc. EUROCON 2008, Computer as a Tool*, pp. 263–267.

[4] T. G. Wilson, Jr., "Life after the schematic: The impact of circuit operation on the physical realization of electronic power supplies," *Proc. IEEE*, vol. 76, no. 4, pp. 325–334, Apr. 1988.

[5] N. Mohan, W. P. Robbins, P. Imbertson, T. M. Undeland, R. C. Panaitescu, A. K. Jain, P. Jose, and T. Begalke, "Restructuring of first courses in power electronics and electric drives that integrates digital control," *IEEE Trans. Power Electron.*, vol. 18, no. 1, pp. 429–437, Jun. 2003.

[6] P. T. Krein and P. W. Sauer, "An integrated laboratory for electric machines, power systems, power electronics," *IEEE Trans. Power Syst.*, vol. 7, no. 3, pp. 1060–1067, Aug. 1992.

[7] R. C. Panaitescu, N. Mohan, W. Robbins, P. Jose, T. Begalke, C. Henze, T. Undeland, and E. Persson, "An instructional laboratory for the revival of electric machines and drives courses," in *Proc. IEEE Power Electronics Specialists Conf. 2002*, pp. 455–460.

[8] J. L. Hudgins, A. Monti, and R. Dougal, "Control system laboratory: A power electronics teaching experience," in *Proc. IEEE-COMPEL 2002*, pp. 112–116.

[9] R. Balog and P. Krein, "A modular power electronics instructional laboratory," in *Proc. IEEE Power Electronics Specialists Conf. 2003*, pp. 455–460.

[10] N. Mohan, *First Course on Power Electronics*. Minneapolis, MN, USA: Power Electronics, 2003.

[11] N. Mohan, A. K. Jain, P. Jose, and R. Ayyanar, "Teaching utility applications of power electronics in a first course on power systems," *IEEE Trans. Power Syst.*, vol. 19, no. 1, pp. 40–47, Feb. 2004.

[12] N. Mohan, P. Jose, T. Brekken, K. Mohapatra, W. Sulkowski, and T. Undeland, "Explaining synthesis of three-phase sinusoidal voltages using SV-PWM in the first power electronics course," in *Proc. IEEE Workshop Power Electronics Education 2005*, pp. 40–44.

[13] T. K. A. Brekken and N. Mohan, "A flexible and inexpensive FPGA-based power electronics and drives laboratory," in *Proc. Power Electronics Specialists Conf., 2006*, pp. 1–4.

[14] S. B. Leeb, M. Alvira, R. W. Cox, J. J. Cooley, J. L. Kirtley, Jr., and S. R. Shaw, "Build to win: A hands-on approach to undergraduate instruction in power electronics," in *Proc. IEEE Power Electronics Education Workshop (PEEW) 2007*.

[15] M. Alvira, "Courseware development for a laboratory class in power electronics," M.Eng. thesis, Dept. Elect. Eng. Comput. Sci., Massachusetts Inst. Technol., Cambridge, MA, USA, Jun. 2005.

[16] J. J. Cooley, "Multifunction Signal Generator for Power Electronics," MIT EECS Advanced Undergraduate Project, Dept. Elect. Eng. Comput. Sci., Massachusetts Inst. Technol., Cambridge, MA, USA, Jun. 2005.

[17] International Rectifier, *IR2125 Gate Driver Data Sheet* [Online]. Available: http://www.irf.com/product-info/datasheets/data/ir2125.pdf

[18] E. Tung, "A Configurable 3-Phase Machine for Laboratory Instruction," M.Eng. thesis, Dept. Elect. Eng. Comput. Sci., Massachusetts Inst. Technol., Cambridge, MA, USA, Jun. 2006.

[19] PSoC 4 Manual and Specification, Cypress Semiconductor Corporation [Online]. Available: http://www.cypress.com/?id=4749

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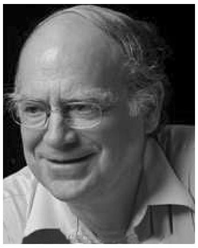

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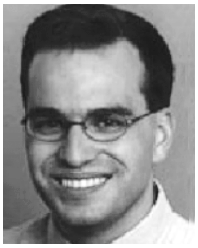

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