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Modern Laboratory-Based Education for Power Electronics and Electric Machines

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Abstract—The study of modern energy conversion draws upon a broad range of knowledge and often requires a fair amount of experience. This suggests that laboratory instruction should be an integral component of a power electronics and electric machines curriculum. However, before a single watt can be processed in a realistic way, the student must understand not only the operation of conversion systems but also more advanced concepts such as control theory, speed and position sensing, switching signal generation, gate drive isolation, circuit layout, and other critical issues. Our approach is to use a *blue-box* module where these details are pre-built for convenience, but not hidden from the students inside a *black box*. Recent improvements to our *blue-box* modules are described in this paper and include a dual-MOSFET control box with independently isolated FET devices, a triple silicon controlled rectifier control box, a discretely built, high quality pulse-width modulation inverter, a small discrete brushless dc drive system, and a high-performance computer-controlled brushless dc dynamometer motor drive system. Complete details, sufficient to allow the reader to duplicate these designs, are publicly available.

Index Terms—Education, educational technology, energy conversion, power engineering education.

I. INTRODUCTION

POWER electronics and motor drives are appropriate subjects for an advanced undergraduate or beginning graduate course. The subject is largely application-driven but draws from a broad knowledge base including basic circuits and electronics, control systems, power systems, and semiconductor devices. For many students, a power electronics laboratory can provide an early experience in synthesis, requiring them to use knowledge across their full curriculum with close attention to detail. It is well known that issues such as wiring configuration, circuit layout, and device selection can dominate the performance of a converter. Similarly, the study of electric machines requires practical demonstration so that students learn power flow and energy conversion concepts intuitively. This suggests that laboratory instruction has great value as a component of a power electronics and electric machines curriculum.

Electric machinery is a topic that is overdue for a renaissance in education. Not only are new machines being developed, but the use of electric machines in general is changing. Traditional curricula focus on dc machines and sinusoidal steady-state ac machines, appropriate for bulk ac power systems. However, modern power systems comprise not only the "grid," but extend to automotive, computer, and shipboard power systems, where ac and dc distribution are used increasingly with electronic drives.

To address this need in a revised electric machinery curriculum, we asked the question, "What does a typical electrical or computer engineer need to know about machines?" Since today only a small number of graduates will be designing machines or drives, but almost all students will interact with machines (bulk power systems, control systems, robotics, microelectromechanical systems, automotive systems, etc.), a revised curriculum should focus on broad applications. To support broader-based education in machinery and power electronics, laboratory changes were made at the University of Illinois at Urbana-Champaign (UIUC).

A. Educational Challenge

A drawback to power electronics laboratory work is that extensive background effort is required before complete working systems can be built. Gate drives, supply isolation, layout, control functions, and other issues must be addressed before a single watt is delivered. A potential source of frustration is to spend several weeks in the laboratory preparing the first fully functional converter. Similarly, modern electric machines and modern applications of electric machines typically involve advanced sensing and control strategies and specialized power electronics circuits. Sophisticated equipment is needed to adequately demonstrate all operating regimes of the test machine but too much integration limits insight into the machine fundamentals.

One way to address these challenges is to take a *black-box* approach: students assemble experiments using pre-built function modules. This approach is common among commercial vendors of power electronics laboratory equipment. It can lead to rugged, sophisticated units that can perform high-level power conversion functions. The obvious drawback of a black-box approach is that without access, it is difficult for students to understand the inner workings—the heart of real power-conversion systems.

An alternative is the *blue box* introduced in [1]. This differs from a black box in that the internal subsystems are studied prior to use and they are simple enough to understand its basic functionality without having to ignore elements. Students focus on system-level design and eventually can replace the blue box with discrete equivalents to understand the salient design issues. In our power electronics laboratory course, there is a final project
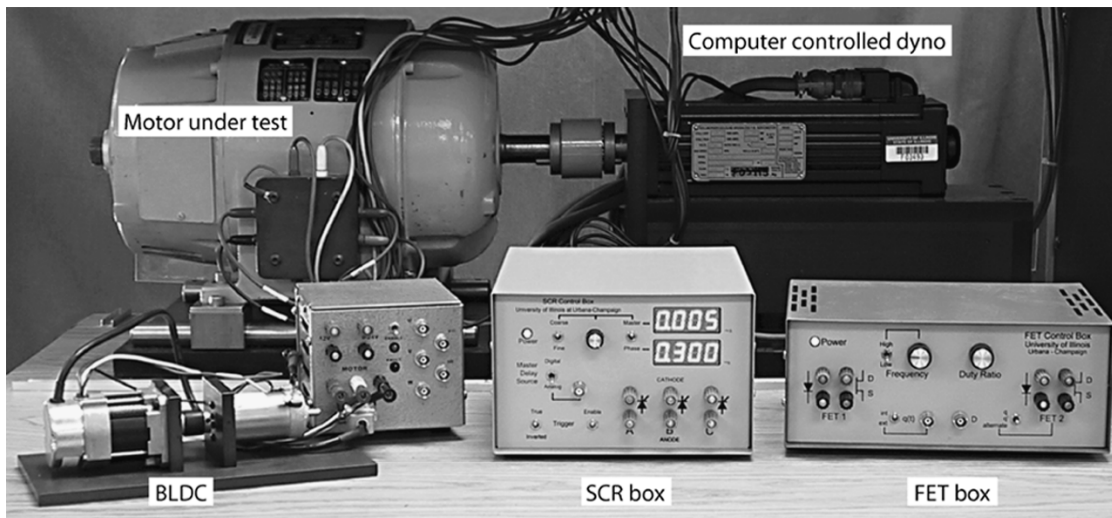
Fig. 1.   Blue box modules: (bottom, left to right) brushless dc motor drive, SCR box, FET box, (top) high performance computer controlled dynamometer.

where the students use the blue boxes only for the initial exploration of the specifications and eventually build a breadboard version implementing the full converter.

The blue-box approach has been used successfully for more than ten years [1], [2]. We have found that the modules help to solidify and de-mystify some fundamental concepts such as gate-drive isolation, PWM generation, control, torque and speed actuators, and speed and position sensing, while at the same time alleviating the burden of implementing them.

B. Alternative Approaches

Since the early 1990s, prompted by dwindling student enrollment, there have been a number of papers addressing educational methods for teaching power electronics and electrical machines. Some of these papers are based on restructuring existing programs. While many academic programs continue to offer the traditional hardware-based laboratory as a supplement to formal lectures, others are opting to forgo the hands-on hardware emphasis in favor of simulation or software-controlled hardware systems. These strategies may be necessary for noneducational reasons such as lack of funds or space to implement a hardware lab but they remove the hands-on experience.

Web-based instructional tools have taken the center of attention recently [3]–[5]. Simulation tools such as Java applets allow students to quickly experiment with "what-if" scenarios. In principle the students gain a deeper understanding of the converter topology by simulating a wide range of operating conditions and component values. In practice, though, it was found [6] that students tended to take an *ad hoc* rather than a methodical approach. Although simulations can be a valuable supplement to formal lecture, they de-emphasize the hardware aspect by avoiding the complexities of converter fabrication. Researchers in power electronics know that experimental verification of theory is almost always necessary—simulation alone rarely suffices to prove anything. The same rigor should be conveyed to our students.

Laboratory-based education in the reported literature generally falls into one of three categories: "system modules," "virtual labs," and "component modules." System modules [7] include the power semiconductors, passive devices, and a switch matrix to realize a number of topologies. They offer the advantages of pre-selected power components and a proven circuit layout. Virtual labs [8]–[11] combine simulation with pre-configured hardware remotely accessed via the internet. Coupled with a simulation package, the remotely controlled and monitored setup allows for direct comparison of simulation and measured data. This hybrid approach is attractive when laboratory space is limited or the requirements of distance learning are considered. Although both the system module and virtual lab approaches return the educational focus to hardware, by having everything predefined the students lose the opportunity to explore passive component selection and design tradeoffs. Remotely located hardware can obfuscate the distinction between simulation and verification. Additionally, units that self-protect artificially alter the behavior of the experimental converter by introducing duty-ratio or frequency limitations. Component modules, such as our SCR or FET "blue boxes" or commercially available units [12] consist of a power device with uncommitted terminals and basic controls. Students provide the reminder of the circuit elements and external wiring. The students are free to choose passive filter components and converter operating mode.

This paper presents recent improvements to the blue-box power electronics and motor instructional laboratories at the UIUC, shown in Fig. 1, that have greatly increased the value of the experimental instruction. The complete design details have been made publicly available to educators who wish to apply our approach.

II. SCR CONTROL BOX

The SCR is an important device in the context of power electronics. From a pedagogical point of view, it represents the natural evolution from diodes and uncontrolled rectifiers to controlled devices. It is typically one of the first power semiconductor devices introduced to students that allows direct control of power transfer. The blue-box philosophy requires a simple conceptual design. Therefore, the SCR box implementation has no innovation in gate drive topology or timing concepts.
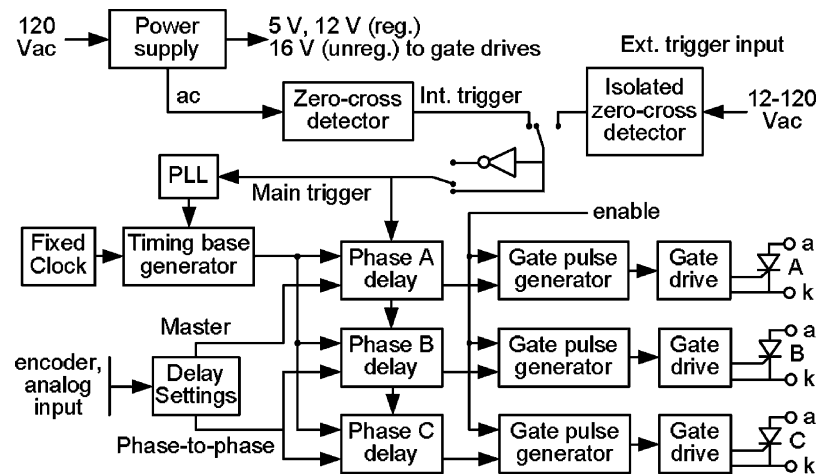
Fig. 2.   SCR box system block diagram.

The new SCR box improves on our previous all-analog design [1] by using a digital design to improve timing stability and allow flexible triggering. These improvements retain a simple conceptual design.

A. Basic Design

A system block diagram of the SCR box is shown in Fig. 2. The control stage generates a main trigger signal used to synchronize the firing of each SCR based on the zero-crossing of either the SCR box power supply voltage or an isolated external trigger. This signal triggers the phase A delay generator and the *master delay* controls the value of the delay. Phase B and C delay generators are cascaded from phase A. The *phase-to-phase delay* controls the delay for phases B and C. These delay settings adjust the number of pulses counted from the time-base generator, representing a particular delay. The time base is either a free-running, fixed-frequency clock used for absolute timing or a frequency-multiplying phase-locked loop (PLL), locked to the main trigger signal, and used for angle-based timing. The output of each phase-delay circuit gates a free-running pulse generator; the gate drive is transformer-coupled to the SCR. Each SCR (10RIA40) is rated at 400 V and 10 A_{ave} (25 A_{RMS}).

The SCR box for instructional labs, shown in Fig. 1, has a simple user interface and a robust design. The digital approach allows calibration-free operation. The gate delays are specified by means of an optical encoder and a coarse/fine switch to allow time-steps of 100 or 5 ms. An analog source also can control the master delay directly through an A/D converter. A trigger inversion switch provides a complimentary gate delay which can facilitate full-bridge operation using two SCR boxes set to the same master delay. For convenience, a trigger-enable switch disables the pulses to the gate drives but otherwise leaves the whole timing sequence undisturbed. The back panel of the box contains the external trigger input and trigger selection switch, not used in our introductory lab course.

B. Example Experiment: dc Transmission System

A dc transmission system is not simple to implement in a student laboratory. A 43-Vac scaled-model dc transmission line can
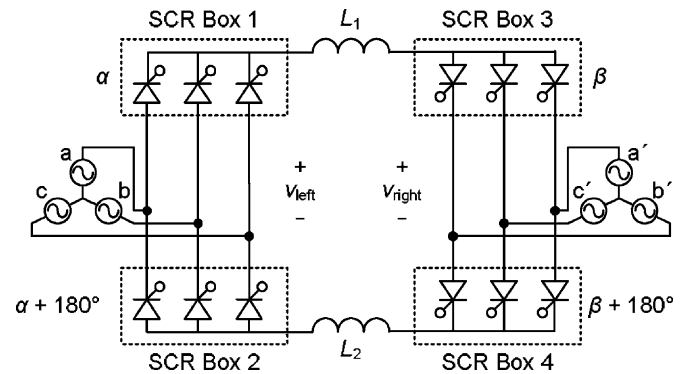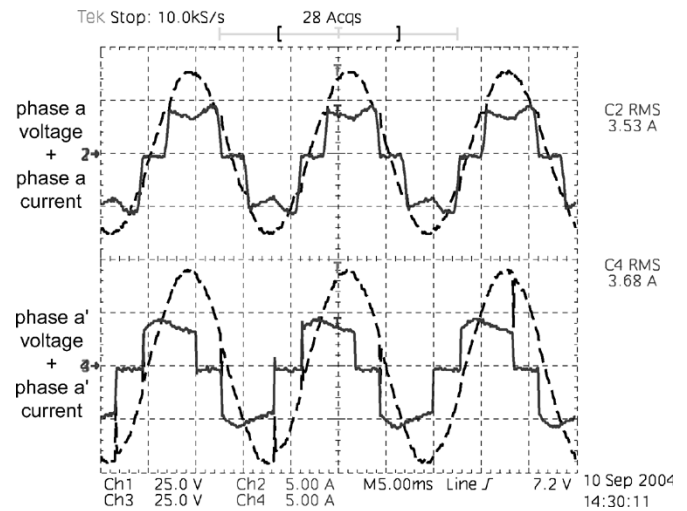

Fig. 3.   Dc transmission line diagram.

Fig. 4.   Dc transmission line phase a input voltage and current, 5 ms/div. Sinusoidal phase voltages 25 V/div, phase currents 5 A/div.

be realized using four SCR boxes as in Fig. 3. Two 25-mH inductors approximate the long transmission line. Since the rectifiers are two-quadrant converters, power flow is bidirectional. Adjustments to the delay angles α and β control real and reactive power at the ends of the line [13].

Fig. 4 shows the measured voltage and current waveforms for phases a and a', corresponding to parameters $\alpha = 0°$ and $\beta = 124°$. The result is a transfer of 185 W at 77% efficiency, a
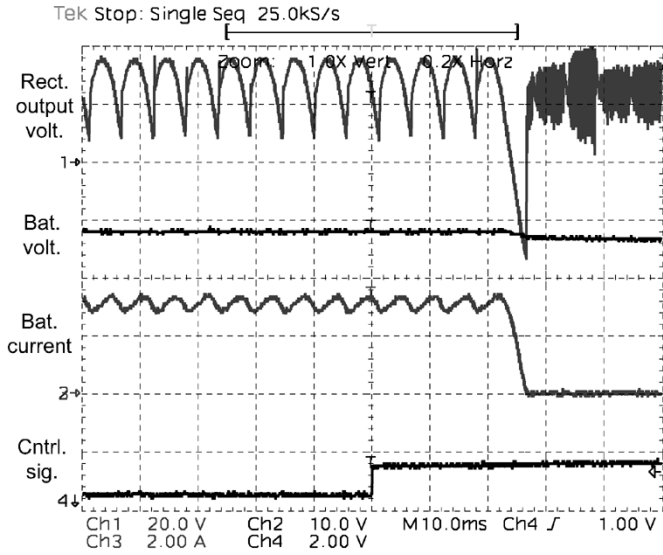
Fig. 5. Battery charger waveforms, 10 ms/div. Rectifier voltage 20 V/div, battery voltage 10 V/div, battery current 2 A/div, control signal 2 V/div.
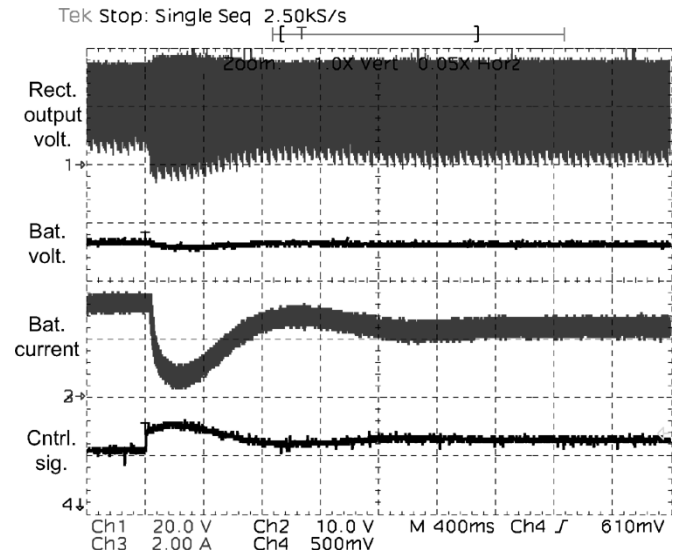

Fig. 6. Battery charger waveforms closed loop, 400 ms/div. Rectifier voltage 20 V/div, battery voltage 10 V/div, current 2 A/div, control signal 0.5 V/div.

4-A link dc current, and 50-V average link dc voltage. The input power factor is approximately 0.94 due mainly to harmonic distortion. The output power factor is approximately 0.6 with a significant displacement angle between the fundamental voltage and current. The low efficiency is mainly due to the ohmic losses in the inductors.

C. Example Experiment: Automatic Battery Charger

The flexibility of the SCR blue box allows closed-loop applications. To demonstrate feedback control, a simple 24-V battery charger was implemented. The circuit is a simple 3-phase half-bridge rectifier connected to the battery by an inductor. A simple control circuit monitors the battery voltage. Fig. 5 shows typical test waveforms for the circuit. When the prescribed battery voltage is reached, the control signal goes high and charging is stopped. Hysteresis ensures that charging will not resume until the battery voltage dips sufficiently. An open-loop version of this experiment is explored by students during normal lab work while the closed-loop version is typically implemented as a final design project. A more complicated control circuit uses battery voltage and current information to monitor state-of-charge (voltage) and track a reference charging current. The nonlinear control law is

$$\alpha = \alpha_0 + k_1 e + k_2 \int e\,dt$$
$$e = i_{\text{bat}} - i_{\text{ref}}$$
$$i_{\text{ref}} = k_0 v_{\text{comp}}$$
$$v_{\text{comp}} = \begin{cases} V_0 & v_{\text{bat}} < v_{\text{ref}} \\ 0 & v_{\text{bat}} \geq v_{\text{ref}} \end{cases} \tag{1}$$

where α_0 is a nominal delay angle, V_0 a reference voltage, and k_0, k_1 and k_2 controller gains. The delay angle α is limited to specified minimum and maximum values. Both v_{bat} and i_{bat} are low-pass filtered before being used in the control law. This control law is easily implemented with three opamps, a comparator and passive components. Fig. 6 shows the battery charger response to a commanded step change in charging current.

III. FET CONTROL BOX

While the SCR allows students to control its turn-on time only, the power MOSFET allows control of both turn-on and turn-off. A new dual-MOSFET blue box has been developed that can implement nearly any dc-dc or dc-ac converter. Like the earlier design [1], the new FET box contains a simple PWM controller with frequency and duty ratio inputs. The important new features are two independently isolated MOSFETs and flexible switching controls. It is essential to the *blue box* concept that there not be any "hidden" functions or control action. Protection is deliberately kept to the absolute minimum—the box does not "self-protect" or use additional complicated circuitry to mitigate errors.

A. Basic Design

A system block diagram of the new FET box is shown in Fig. 7. Without external over-voltage or over-current circuitry to protect the FET, high-current and high-voltage rated FET devices are required. This implies high $R_{\text{ds(on)}}$ given current technology. The FET selected (IRFP360) is rated at 400 V, 23 A, 0.2 Ω $R_{\text{ds}}(\text{on})$. The high on-state resistance is the compromise required for a design to achieve a broad range of applications. A simple lossy snubber helps to limit the MOSFET transient voltage. The auxiliary diode (MUR3040PT) is rated for 400 V, 30 A. The drain, source, anode, and cathode terminals are left uncommitted and brought to the front panel for arbitrary connection into the student's circuit. The FET box is designed to process several hundred watts of power.

Electrical isolation is an important aspect of the FET box design to allow each MOSFET to be arbitrarily placed within any topology: high-side, low-side, reversed, series-connected, negative supply voltage, etc. Further, each of the two MOSFETs must be independently electrically isolated. Safety considerations require that the control and the inputs be ground referenced. To meet these requirements, the internal power supply uses a multiple-output flyback converter. Power is obtained from either the
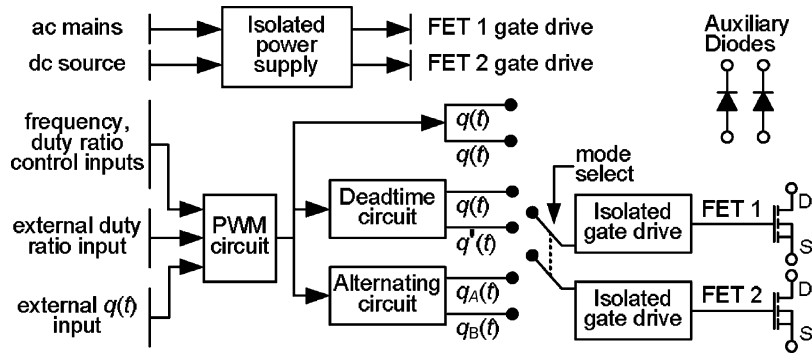
Fig. 7.　FET box system block diagram.

mains voltage via an internal step-down transformer or an external dc source. The output of the flyback converter consists of two isolated 14-V gate-drive supplies and ground-referenced 12-V and 5-V supplies for the controls.

The control section of the FET box is based on the SG3526 PWM IC. This particular IC is widely used because of its linear PWM action, wide frequency range, and ease of synchronization. Frequency and duty ratio are controlled via front panel knobs for typical implementation, shown in Fig. 1. If modulation of the duty ratio is desired, as in a PWM inverter or to implement a control loop, a duty ratio "D" BNC connector overrides the duty ratio knob. The internal PWM process can be bypassed and an externally generated switching function used via the "$q(t)$" BNC connector.

To allow maximum flexibility, the control circuit contains simple logic that can be selected to operate the MOSFETs one of three modes.

- "Matching mode" [q,q]: both MOSFETs operate with the same switching function—used for parallel operation or for full-bridge circuits with two boxes.
- "Complementary mode" [q,q']: MOSFETs operative in complement with a short dead-time—used for half-bridge and synchronous-rectifier converters, two-quadrant dc-dc converters, and other dual-switch circuits.
- "Alternating mode" $[q_A, q_B]$ MOSFET switching alternates—used for push-pull converters.

These three choices allow the realization of almost any dc-dc converter, including direct, indirect, flyback, and most two-switch forward converters. Two-switch dc-ac converters such as voltage-sourced and half-bridge PWM inverters are also possible. Multiple FET boxes can be ganged together in master/slave configuration via the "$q(t)$" BNC connector to support full-bridge forward converters, full-bridge inverters, and ac-ac converters.

B. Example Experiment: Buck Converter

The buck converter is a straightforward dc-dc topology studied in a first power electronics course. However, the high-side switch complicates controlling the circuit. In lab, the students use the FET box as a single high-side switch. The uncommitted auxiliary diode is wired as the freewheeling diode. External bypass capacitors, the choke, load resistor, and smoothing capacitor are all that are required to complete the circuit. Typical waveforms the students observe are shown in
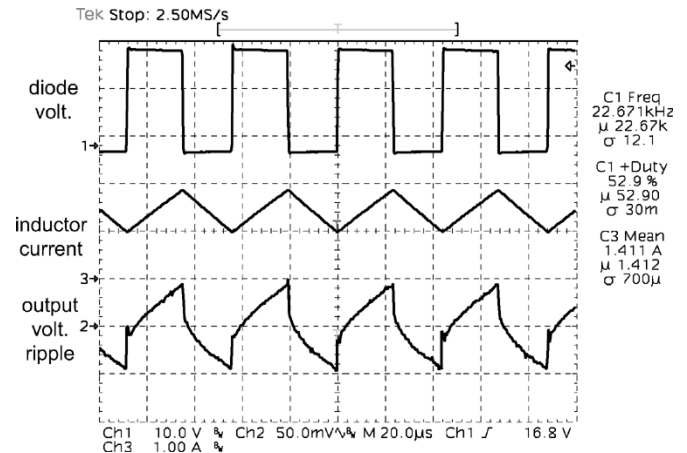

Fig. 8.　Experimental buck converter, 20 μs/div. Diode voltage 10 V/div, inductor current 1 A/div, ripple voltage 50 mV/div.

Fig. 8. The performance of the system is sufficient to observe salient features such as the ESR jump of the output capacitor (bottom trace).

The compromise in power device selection implies that a single FET circuit designed to process hundreds of watts will be inefficient at tens of watts. In the lab, a 48-V to 12-V converter is used to measure the efficiency of the FET blue box over the range of a few watts to about 100 W. Using standard components available to the students, efficiencies greater than 80% can easily be obtained. Students are encouraged to explore the effect of switching frequency on converter efficiency.

C. Example Experiment: ac-ac Conversion

Ac to ac conversion is perhaps the most general energy transfer in power electronics. In the past, bulky motor-generator sets provided frequency conversion and line frequency transformers provided voltage conversion. Even today, with solid-state switching devices, direct ac-ac conversion is nontrivial. Fundamental to the problem is the requirement for bilateral switches—the switch is required to carry current or block voltage of either polarity. Because of this and the control complexity, most first-level courses do not discuss direct ac-ac conversion. Even most commercial ac-ac converters bypass these requirements by utilizing a dc link.

Direct ac-ac switching achieves frequency conversion by connecting the source and load through a switching matrix and operating the switches such that $f_{out} = f_{switch} \pm f_{in}$. The
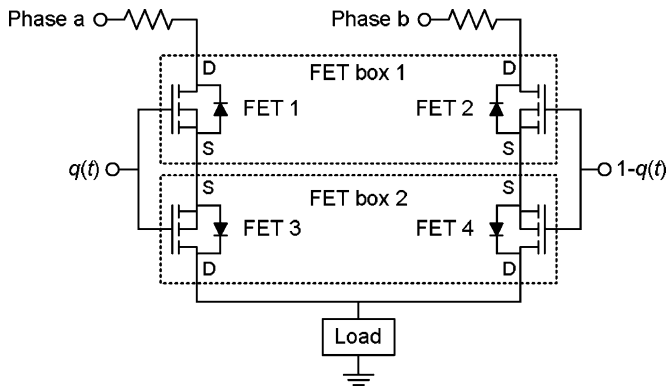
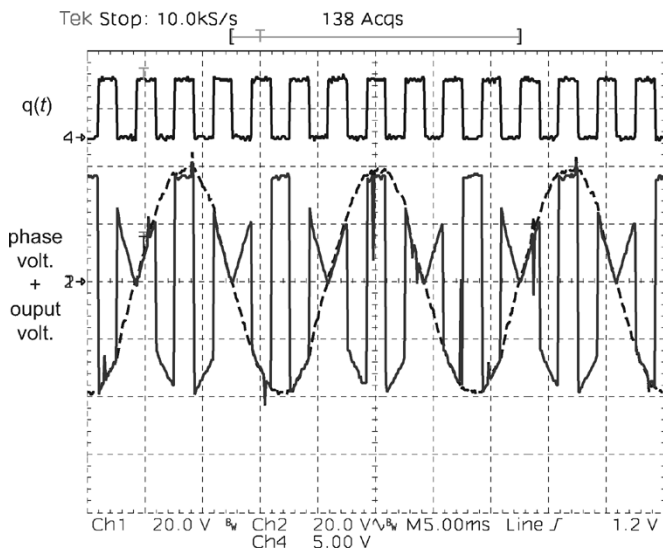Fig. 9.   Direct ac-ac conversion using two FET boxes.

Fig. 10.   Experimental "universal frequency changer," 5 ms/div. Phase voltage and output voltage 20 V/div.

full-bridge circuit shown in Fig. 9 is realized by using two FET boxes and a function generator. The FET boxes are both connected to the function generator via the $q(t)$ BNC connector selected to *external*. FET 2 on both boxes is selected to operate in $q'(t)$ mode to internally generate the complementary switching function (plus some dead-time.) Each auxiliary diode is wired anti-parallel to provide a freewheeling current path.

Typical measured waveforms for a "universal frequency changer" are shown in Fig. 10. The external function generator provided a TTL compatible 50% duty ratio square wave set to 300 Hz, shown at the top of the figure. Phase voltages were obtained from a 120:25 Vac center-tapped secondary transformer. The "chopped" 60 Hz results in an output with equal magnitude frequency components at 240 and 360 Hz and is shown superimposed on one phase voltage for reference. A switching frequency less that the phase frequency results in a "slow switching frequency converter." The external function generator allows arbitrary frequency conversion to allow students to easily experiment with frequency-based speed control of small ac machines.
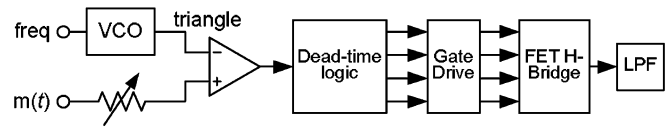

Fig. 11.   PWM amplifier block diagram.

IV. PULSEWIDTH MODULATION INVERTER

The FET box allows students to configure a half-bridge inverter and an audio signal modulating function to build a class-D amplifier. While the sound quality is not perfect (qualitatively it is about equivalent to AM radio), this application impresses the students with the broader possibilities for PWM power conversion.

A full-bridge PWM inverter is a complicated circuit to build with discrete components in an undergraduate laboratory class, particularly when linearity and other performance attributes are considered. While PWM ICs are common enough, the essential elements of the PWM process are often buried inside the chip and inaccessible. The extra circuitry for soft start, overload protection, and control, means that PWM ICs do not emphasize the fundamentals of the process as well as the salient features of implementing a full bridge inverter.

A. Basic Design

In the new blue-box PWM inverter, all aspects of the PWM process are implemented using discrete components. A block diagram of the process is shown in Fig. 11. Test points identifiable by color and number are provided so that students can examine the triangle carrier waveform, the input modulating waveform, the resulting PWM waveform of the comparator, the four gate-drive signals, the bridge output voltage, and the output voltage of the on-board low-pass filter. The triangle carrier frequency can be adjusted from tens of kilohertz to over 200 kHz and has an amplitude appropriate for audio line-level of about 2 V_{pp}. Analog input is supplied through the 3.5-mm stereo headphone jack, the left and right channels are summed into a mono signal. To ensure correct dc biasing the analog input is ac coupled. The "volume knob" is simply an attenuator for the input signal. In order to keep the circuit as simple as possible, all gate-drive signals are ground referenced. While this limits the bridge voltage to about 20 V ($V_{\mathrm{gs}}(\max)$ for the output FETs), sufficient power can be processed to drive a small speaker. In another experiment, students use the PWM amplifier as an inverter to drive a small ac motor through a step-up transformer.

Fundamental to the discussion of inverters is the issue of dead-time. While any practical implementation of an H-bridge inverter must incorporate dead-time for FET switching, this is often treated as an advanced topic not explored in an introductory level power electronics class. Specialty gate-drive ICs provide the functionality but obscure the operation. In contrast, the blue-box inverter uses simple delay-based dead-time generation—easy for students to understand and easy to motivate as an essential element of operation. Dead-time is realized in discrete logic with Schmitt inverters, AND logic gates, and a single R-C circuit. Test-points on the printed circuit board (PCB) allow each gate-drive signal to be observed during operation.
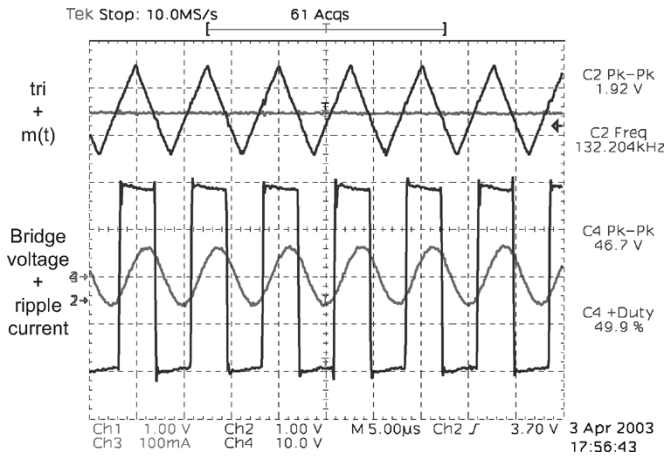
Fig. 12. Experimental PWM process waveforms, $5\,\mu s/\mathrm{div}$. Triangle and $\mathrm{m}(t)$ 1 V/div. Bridge voltage 10 V/div, load ripple current 100 mA/div.

Key components were chosen to allow construction of high quality, highly linear, PWM with respect to the modulating function. The low-pass output filter was designed with a cut-off frequency of 20 kHz. The result is a PWM process with enough quality (audio fidelity) to substitute for many commercial audio amplifiers.

B. Example Experiment

Students explore the class D audio amplifier by using a CD player to supply music as the modulating function and a moving coil speaker as the load. The quality is much higher than that attainable with the FET box and emphasizes all attributes of PWM as a high-quality power conversion control process.

In Fig. 12, an example of a 132-kHz triangle carrier wave with a superimposed continuous dc modulating function is shown. The resulting 40 V_{pp} bridge square wave with constant 50% duty ratio and associated current ripple of the output filter is shown for an 8 Ω speaker.

V. DISCRETE BRUSHLESS DC MOTOR/INVERTER SET

Traditional electric-machines courses focus on fixed-frequency machines, the mainstay of industrial applications. Recently, however, permanent magnet synchronous machines (often called brushless dc, or BLDC, machines) have become important, replacing brushed dc machines in applications requiring high efficiency and small size. BLDC machines differ from other electric machines in a fundamental way: electronics are required to commutate. The BLDC system is a convenient way to apply the blue-box concept to the study of electric machines. It uses a simple inverter to introduce power electronic concepts and frequency control methods in a variable-speed motor drive.

A. Basic Design

A small system, shown in Fig. 13, has been developed that illustrates the energy conversion process in a brushless dc motor/inverter combination. The motor is small (40 W) and portable. A dynamometer has been built that couples the brushless dc motor to a permanent magnet dc machine, which is used as a generator to apply load. A simple inverter commutates the
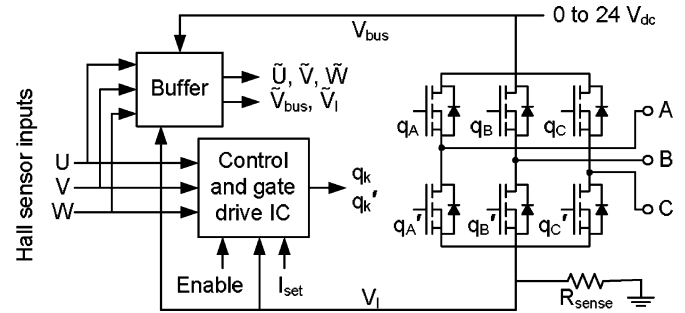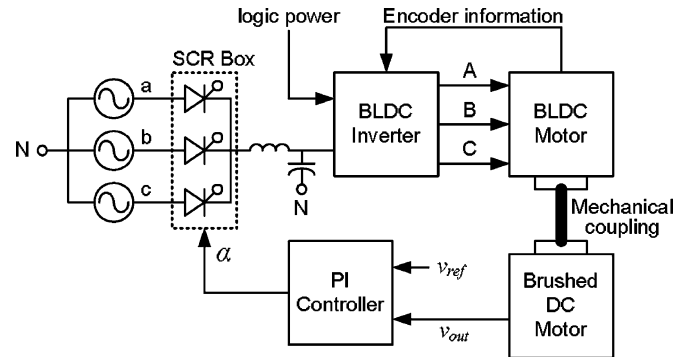

Fig. 13. BLDC system block diagram.

Fig. 14. BLDC speed control experiment diagram.

motor. The user supplies logic power (12 V) and dc bus voltage (0–24 V). The variable bus voltage determines the speed of the machine, similar to the armature voltage of a separately-excited brush dc motor. An enable switch and an over-current fault indicator are provided. Using the Hall tracks on the encoder, a simple logic circuit sequences the three-phase inverter to switch the bus voltage across the appropriate windings of the machine. All signals are provided as buffered outputs so that students can examine the relationship between shaft position, bus voltage, and phase current at various speeds and loads to further understand the physical processes involved.

This simple inverter can be used generically for other small-motor control and dc-ac converter applications as well. No compromises have been made that limits the PWM process to motor frequencies. Using an external circuit to generate the PWM signal, the drive could be connected to a low-voltage induction machine, a generic RL load, or another brushless dc machine (with proper synchronization in the external circuit).

B. Example Experiment

A simple experiment that can be implemented with the brushless dc inverter is shown in Fig. 14. A 3-phase half-bridge controlled rectifier feeds the power input of the inverter. The inverter generates the phase voltage waveforms for the brushless dc motor which is coupled to a brushed dc generator. The generator voltage is the input to a PI controller. The output of the PI controller is the input to a SCR box, controlling the delay angle α of the rectifier to track a given generator voltage reference.

Fig. 15 shows typical measured waveforms for the experiment at a bus voltage of 9 V. The brushed dc machine is loaded with a 43 Ω resistor. Bus information shown is from the inverter
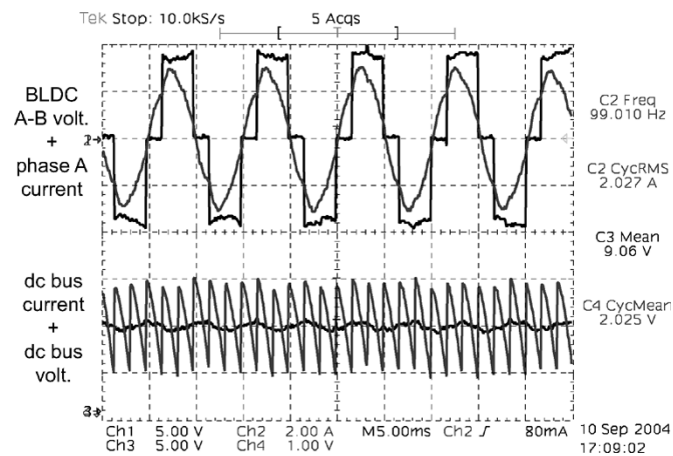
Fig. 15.   BLDC sample waveforms, 5 ms/div. BLDC voltage 5 V/div, current 2 A/div. Dc bus voltage 5 V/div, current 1 A/div.

outputs. Phase current is nearly sinusoidal, with harmonics corresponding to the quasisquare-wave excitation. Ripple in the bus voltage corresponds to both inverter switching frequency and rectifier frequency.

VI. HIGH-PERFORMANCE COMPUTER CONTROLLED PERMANENT MAGNET SYNCHRONOUS MACHINE DYNAMOMETER SYSTEM

While the brushless dc system has the flexibility to drive several small machines, it is not well-suited for use as a torque actuator and cannot drive larger machines. A four-quadrant, dynamically-rapid dynamometer system facilitates understanding of the complete operation of an electric machine including dynamic performance. Such a system can demonstrate all regions of steady-state operation of a test machine and also precisely demonstrate dynamic performance for tests such as step loads, speed or position dependent torque (to simulate real loads), and control dynamics. Commercially available dynamometers are expensive and, although optimized for precision steady-state measurements, offer little flexibility and hide the inner workings of the system. Because of this they are not well suited for an instructional environment.

As in many traditional educational labs, our previous setup used a brushed dc machine with a drive. Since it was simply a speed actuator with minimal four-quadrant operation, the potential experiments were limited. Drive control and data recording was done manually. To improve our instructional laboratory, we have installed specialized dynamometers that act as arbitrary speed or torque generators.

This system offers the same advantages for an electric-machines laboratory that the SCR and FET box provides for a power-electronics laboratory—the students concentrate on understanding the experiment without having to spend time and effort in obtaining the desired speed or torque. Although the dynamometer system might seem simple, its ability to provide an arbitrary speed or torque cannot be underestimated. Researchers with electric machine experience recognize that obtaining an arbitrary torque from traditional machine setups, even in steady state, is not simple.
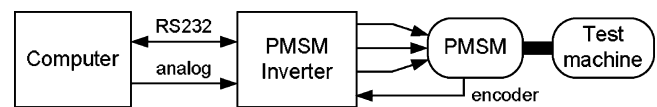

Fig. 16.   Computer controlled dynamometer system diagram.

A. Basic Design

The system block diagram of our new dynamometer system is shown in Fig. 16. A commercial (Kollmorgen SR-10 200), 4 kW, PMSM controller was used to provide the actuation method and control interface. The PMSM used (Kollmorgen B-206-C21) is rated for 230 V, 10 A, 4900 RPM, and 6.44 N·m. The controller itself has several features that are useful to demonstrate to students, since it integrates a power-electronics three-phase inverter and a position detector with multiple output modes. The response time of the torque control (in the millisecond range) makes the system suitable not just as a steady-state friction-like load, but as a dynamic load that can have transients or a programmed torque-speed characteristic, capabilities that are advantageous over conventional educational lab dynamometers.

The controllers include digital and analog control ports. Interface software (implemented in Labview) commands the controller through a data acquisition card. The interface, shown in Fig. 17, is high-level and allows students to directly input the desired torque or speed. Readouts are given on bench instruments and on the computer screen. Tedious or delicate tests (such as induction-motor torque-speed curves) can be implemented automatically. Full details of this system are discussed in [14].

B. Example Experiment: Synchronous Machine "V" Curves

A basic example that illustrates how the students use the system is the synchronous machine "V" curve experiment. Using the software interface, students adjust the torque or speed in order to conduct the experiment and collect data from the interface and external meters. Fig. 18 shows the resulting "V" curves for a 230 V, 9 A, 1.5 kW, six-pole synchronous machine operating as a motor and loaded by the dynamometer system. Each curve corresponds to a given constant load torque and shows how armature current behaves as field excitation of the machine is changed. The experiment clearly shows the significance of the dynamometer system. A precise torque can be commanded and the students can concentrate on understanding the experiment.

VII. "BLUE BOX" DESIGN DETAILS

An important objective of the blue-box project was to make publicly available all details to educators who wish to apply this approach. While this paper presents the context of the blue-box project, the full design information is available separately in the form of a detailed technical document [15]. Complete circuit diagrams and parts lists are given in [15]. Full details including the theory of operation, schematics, PCB artwork, mechanical drawings, and bill of materials, are publicly available in [15], electronically via the web [16], or directly from the authors. We intend these details to be sufficient to allow the reader to duplicate all the blue-box modules.
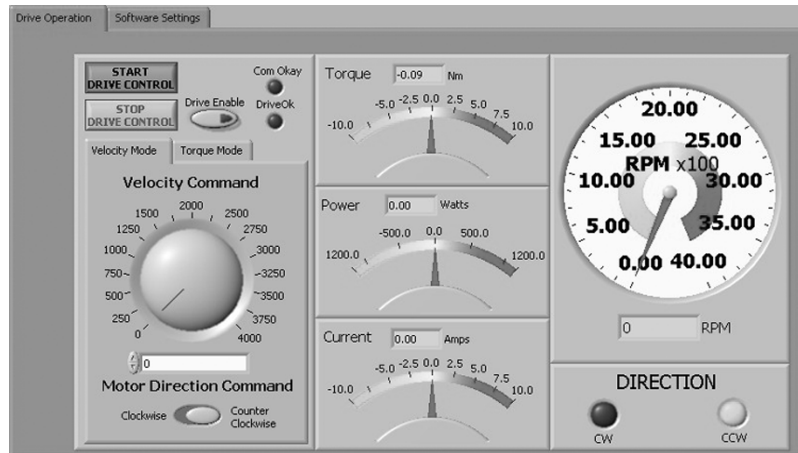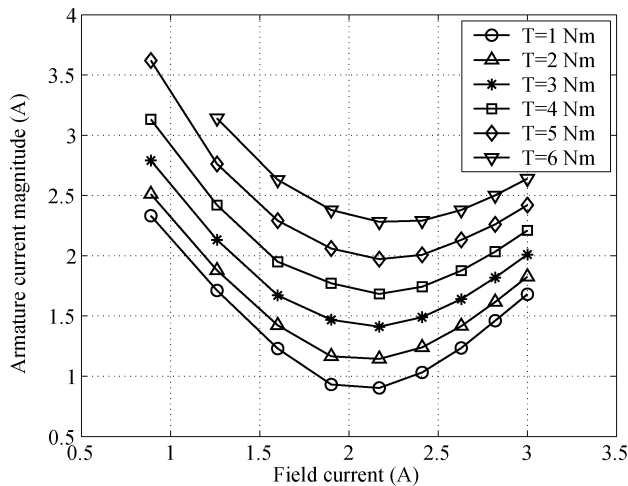
Fig. 17.   Drive control user interface.

Fig. 18.   Experimental "V" curves for a synchronous machine.

Component-level schematics of the complete circuits were designed using Cadence OrCAD Capture, and printed circuit board design was done using Cadence OrCAD Layout. The schematics and PCB artwork are publicly available [15], [16]. Mechanical design for the enclosures was done using Autodesk Inventor and Microsoft Visio. These designs along with additional details such as artwork for the silkscreen and fabrication drawings for mechanical parts are provided in [15], [16]. Application examples with photographs and typical waveforms are shown in [16].

VIII. CONCLUSIONS

New blue-box designs for undergraduate power-electronics and electric-machines instructional laboratories have been described. An SCR box enables an in-depth study of line-commutated circuits, including ac-dc, dc-ac, and ac-ac conversion. A dual MOSFET box supports an unlimited range of dc-dc, dc-ac, and ac-ac circuits with a clear and simple circuit that can be fully understood by students as they use it. A full-bridge PWM inverter allows students to get "deep inside" a real PWM process to see how high-quality power conversion works. A simple dynamometer system introduces the interrelation of power electronics and electric machines in the context of a small BLDC system. A sophisticated, computer-controlled dynamometer system simplifies the study of electric machines of all types. Together, these components comprise a valuable aid to teaching power electronics and electric machines that emphasize the practical aspects of design on par with theory.

REFERENCES

[1] P. T. Krein, "A broad-based laboratory for power electronics and electric machines," in *Rec., IEEE Power Electronics Specialists Conf.*, 1993, pp. 959–964.
[2] P. T. Krein and P. W. Sauer, "An integrated laboratory for electric machines, power systems, and power electronics," *IEEE Trans. Power Syst,*, vol. 7, no. 3, pp. 1060–1066, Aug. 1992.
[3] U. Drofenik and J. W. Kolar, "Survey of modern approaches of education in power electronics," in *Proc. IEEE Applied Power Electronics Conf.*, vol. 2, 2002, pp. 749–755.
[4] F. A. S. Gonvalves and C. A. Canesin, "JAVA applets for a WWW-HTML-based course in power electronics," in *Rec., IEEE Power Electronics Specialists Conf.*, vol. 1, 2001, pp. 85–90.
[5] U. Drofenik and J. W. Kolar, "Interactive Power Electronics Seminar (iPES)-a web-based introductory power electronics course employing Java-applets," in *Rec., IEEE Power Electronics Specialists Conf.*, vol. 2, 2002, pp. 443–448.
[6] D. A. Torrey, "A project-oriented power electronics laboratory," *IEEE Trans. Power Electron.*, vol. 9, no. 3, pp. 250–255, May 1994.
[7] 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, Jan. 2003.
[8] K. W. E. Cheng, C. L. Chan, N. C. Cheung, and D. Sutanto, "Virtual laboratory development for teaching power electronics," in *Rec., IEEE Power Electronics Specialists Conf.*, vol. 2, 2002, pp. 461–466.
[9] L. de V. B. Machado Neto, F. M. de Souza, R. C. Figueiredo, and R. C. Ivo, "Power electronics laboratory at PUC Minas/Brazil: simulation and experiment's tools," in *Proc. IEEE Frontiers in Education Conf.*, vol. 2, 2000, pp. S1E/1–S1E/6.
[10] A. Etxebarria, I. J. Oleagordia, and M. Sanchez, "Power electronics and basic electronics real experiments through the World Wide Web," in *Proc. IEEE Frontiers in Education Conf.*, vol. 3, 2001, pp. F4D–F11.

[11] C. Fernandez, O. Garcia, J. A. Cobos, and J. Uceda, "Self-learning laboratory set-up for teaching power electronics combining simulations and measurements," in *Rec., IEEE Power Electronics Specialists Conf.*, vol. 2, 2002, pp. 449–454.

[12] Semikron, Inc.. (2004) Semiteach. [Online]www.semikron.com

[13] J. G. Kassakian, M. F. Schlecht, and G. C. Verghese, *Principles of Power Electronics*. Reading, MA: Addison-Wesley, 1992, pp. 240–249.

[14] N. R. Hakes, "Automated Calibration and Control of a Permanent Magnet Synchronous Machine and Drive,", Tech. Rep. UILU-ENG-2003-2509, CEME-TR-03-04, Oct. 2003.

[15] R. S. Balog, J. W. Kimball, Z. Sorchini, P. T. Krein, and P. L. Chapman, "'Blue Box' Power Electronics Control Modules for Laboratory Based Education,", Tech. Rep. UILU-ENG-2004-2504, CEME-TR-04-02, Jun. 2004.

[16] J. W. Kimball, R. S. Balog, Z. Sorchini, and P. T. Krein. (2004) The Blue Box Project at the University of Illinois at Urbana-Champaign. Univ. Illinois at Urbana-Champaign. [Online] Available: http://www.energy.ece.uiuc.edu/blueboxes/index.htm

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