

A Laboratory Component of a Switching Power Supply Course Requiring Nominal Resources

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Abstract – A graduate electrical engineering technology course in switching power supply design was created with a laboratory component having a practical focus. Important goals for the course were to avoid the use of specialized laboratory equipment and to select experiments minimizing the usual safety concerns associated with high voltages and currents. Furthermore, the course and laboratory component emphasized the close coupling of theory, simulation, fabrication and testing. Several of the experiments were constant from one semester to the next, and a small project that varies each time is selected that requires students to apply key principles highlighted in the course. The experiments utilize low-power converter circuits based on Linear Technology's controllers and components. This enables students to use that company's free and versatile SPICE-based simulator that includes models of their devices, allowing students to realize simulations that closely match experimental results. It also avoids the need for students to design controller models that often include proprietary functions and circuitry.

Keywords: Switching, Power, SMPS, SPICE, LTSpice.

INTRODUCTION

Power electronics and switching power supplies courses are present in numerous electrical engineering and engineering technology programs and some have been described in the literature [Ang, 1][Shirsavar, 12]. This author designed the course described here independently based on personal industrial experience. As in the author's case, engineers with general electronics backgrounds must often design the power supplies of the system they are designing. With greater emphasis on battery power and efficiency, these supplies increasingly rely on switched-mode power supply (SMPS) design techniques. Typical industrial projects have short schedules and engineers must acquire sufficient knowledge to design the circuits they are responsible for as quickly as possible. SMPS controller integrated circuit (IC) manufacturers such as Linear Technology, Inc. and National Semiconductor, Inc. recognize this and developed computer-aided design software to assist in the design process [Linear, 4][National, 10]. With experience serving as a guide and an awareness of available CAD tools, the Switching Power Supplies course described here was designed to balance theory and application so that upon completion, students would have confidence that they could design, build, test, and troubleshoot SMPS circuits.

The focus here is on the laboratory component of a 15-week semester graduate Switching Power Supplies course for the Electrical and Computer Engineering Technology (ECET) department at Southern Polytechnic State University. Although created for engineering technology students, the laboratory exercises described are just as relevant for an engineering course. Indeed, the ECET department's graduate program has students with both engineering and engineering technology undergraduate degrees. At the time of this course's creation, the department's undergraduate program had not developed a power electronics course and the graduate program's only other power electronics course was designed for electric drive applications.

The laboratory component of a new course is often the most difficult to create. The experiment topics and schedule must be defined to coordinate closely with those of the classroom; the experiment instructions including circuit designs must be created; the laboratory equipment has to be selected to support the experiments; and the

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miscellaneous parts needed for the circuits must be purchased. For power electronics courses in general, safety is a primary concern and everything associated with the laboratory experiments must reflect this priority.

OVERALL COURSE DESIGN

The course term is a 15-week semester, with three hours of class and three hours of lab each week. The course was designed using the following guidelines:

- Cover important switched-mode power supply topics with a practical approach, enabling students to immediately apply the principles in the workplace
- Choose a textbook that has an appropriate combination of theoretical and applied principles
- Ensure that theoretical principles are illustrated through simulations tightly-coupled to experiments
- Select experimental circuits that are representative of those used in commercial applications
- Use only test equipment available in the department's general-purpose electronics laboratories
- Require students to build all of their experimental circuits
- Design the lab experiments to be as safe as possible

The textbook chosen takes a practical approach to the subject and covers all topics relevant to the course, presenting them in a readily-understandable manner [Krein, 2]. It also includes a treatment of SMPS control techniques, allowing the course to include advanced topics. The text provides a good foundation that is easily expanded on as needed. The text is well suited for the target audience that can include students with engineering technology and engineering degrees that may not have a foundation course in power electronics.

It was decided that the course would focus on DC-DC converters. This choice was made because such circuits are ubiquitous; their design principles also apply to AC-DC converters; for low-power designs the controller ICs are inexpensive; and low-power circuits are quite safe to work with. The laboratory component of the course was designed around Linear Technology's LTSpice simulator and their SMPS controller ICs. The simulator includes macromodels of their controller circuits and their analog ICs. It also has numerous example circuits using selected controllers. This meant that the simulations would likely have a good correlation to experimental results, which was a primary objective of the course. Finally, the choices mentioned above allowed the use of general-purpose laboratory equipment available in the average electronics laboratory. The exceptions are the need for a high-quality impedance meter and optionally oscilloscope current probes.

The requirement that students build their experimental circuits means that they must learn to solder pay attention to details. They inevitably make mistakes and therefore will also learn valuable troubleshooting skills. Thanks to the low-power circuits used in the lab, these mistakes are usually benign and do not result in damaged components.

Major topics covered in the course are:

- Switching concepts
- Fourier techniques review
- Standard DC-DC converter topologies (Buck, Boost, Buck-Boost, Boost-Buck, Forward, Flyback, AC-link)
- Inductors and transformers
- Power Semiconductors (Diodes, BJT, MOSFET, IGBT)
- Discontinuous mode operation
- Non-ideal component models
- Inverters (full- and half-bridge)

- Converter feedback control

Students are made aware at the beginning of the course that SMPS design incorporates advanced analog circuit design techniques. The emphasis on non-ideal behavior of circuit elements, particularly inductors and capacitors actually helps students with RF design techniques as well. Since students wind their own inductors, the inductor and transformer lectures also include a lecture on core selection and use of manufacturers' data sheets to choose the correct number of windings, power handling, etc. The treatment of power semiconductors is limited to Diodes, BJTs, MOSFETs, and IGBTs as these are the devices most likely to be used in low-to-medium power DC-DC converters.

COURSE LABORATORY DESIGN

The primary considerations that went into the Switching Power Supply course laboratory component have already been mentioned. The desire to accurately simulate the laboratory circuits that use commercial controller ICs was very important, so it led to the selection of Linear Technology's LTSpice simulator and use of its controller ICs. Therefore, a discussion of the simulator's features that led to this decision is appropriate.

The simulator is full-featured and free of charge. The size of the simulated circuit is limited only by the computer resources and the graphical schematic-entry interface is quite good. The user has a considerable amount of control over the simulation process, including the numerical integration technique employed and the solver tolerances. The parts library includes most, if not all, of Linear Technology's converter, operational amplifier and comparator IC's. The MOSFET library has about 200 parts, the BJT library has about 35 parts, but unfortunately there are no IGBT parts. Numerous other special function parts and models are included. The simulator also has some interesting capabilities, such as the abilities to calculate circuit efficiency and to detect steady-state conditions. A number of example circuits are included as well. Users can easily add transistor and diode component models, allowing the standard libraries to be expanded. Essentially, LTSpice is an excellent simulator that is useful for more than just SMPS simulations. However, the documentation is just adequate.

The importance of having macromodels for the controller ICs cannot be overemphasized. Since the technology used in the IC designs themselves is proprietary, the probability of students creating accurate models of these ICs is vanishingly small. The controllers typically use a combination of voltage and current feedback. They can also use a version of pulse-width modulation that permits pulse skipping and/or a type of pulse-frequency modulation.

The laboratory facility includes eight workstations; and students are organized into pairs working on the same circuit. Exceptions are made for students having access to equipment at home or their workplace. Those students can work alone and are awarded some extra credit for doing so. Each workstation has a 100 MHz Tektronix TDS2012 two-channel oscilloscope, an Agilent E3630A triple-output power supply, and an Agilent 33220A function generator. An Agilent 4263B and a Stanford Research Systems SR720 impedance meter that can measure capacitors and inductors at five or six discrete frequencies up to 100 kHz are shared as needed. Two Tektronix DC current probes are shared by the students. Soldering stations are also provided for circuit construction.

The laboratory exercises include six standard ones that are substantially the same each semester and one small project that varies each semester. The project requires some design elements such as component selection to meet desired specifications. The project circuit topology was given to the students as a starting point. Starting from a known topology and modifying it as needed is a typical approach that an engineer will take when designing a SMPS.

Table 1 lists the laboratory exercises and key features of each along with the number of assigned laboratory hours. The standard exercises primarily focused on use of the LT1172 step-up and the LT1676 step-down converter/controller ICs. The former was used in a 5V-to-12V converter and the latter in a 12V-to-5V converter. The LT1172 and LT1676 were chosen because they were available in through-hole packages for easier construction and they operated at 100 kHz. This corresponded to the maximum frequency setting of the impedance meter used to measure inductor impedance. Therefore, the measured inductor parameters could be included in the simulation.

Table 1. Laboratory Exercises

Exercise Title	Hours	Features
LTSpice Overview	3	Entering schematics, simulation, analyzing results
Simulate LT1172 Step-Up DC-DC Converter	3	Application circuit designed by Linear Technology, explore LTSpice features, start-up transient, load transient, steady state, line & load regulation, ripple, efficiency, switch duty vs. load, ripple spectrum
Simulate LT1676 Step-Down DC-DC Converter	3	Application circuit designed by Linear Technology, start-up transient, load transient, steady state line & load regulation, ripple, efficiency, switch duty vs. load, ripple spectrum
Non-Ideal Inductor	3	Design and build inductors needed for LT1172 and LT1676 circuits, measure inductance & Q with impedance meter at 100 kHz, use tuned-circuit to do same
LT1172 Step-Up DC-DC Converter	6	Build and test circuit simulated earlier. Measure line & load regulation, ripple, efficiency, switch duty vs. load, ripple spectrum. Compare to simulations.
LT1676 Step-Down DC-DC Converter	6	Build and test circuit simulated earlier. Measure line & load regulation, ripple, efficiency, switch duty vs. load, ripple spectrum. Compare to simulations.
Project	12	Capstone in nature. Features depend on specifications.

The course was taught three times to date and three different semester projects have been assigned: a flyback converter, a single-ended forward converter, and an inverter with voltage feedback control. The first two required the same LT1172 step-up controller used in the standard lab exercises. These two circuits were based on ones found in Linear Technology application notes. For the inverter, the author designed a circuit, giving the students a schematic and requiring them to select components to meet desired specifications. The inverter project included a mandatory half-bridge circuit that could be expanded for extra credit. For extra credit, the half-bridge was converted to a full bridge and for even more extra credit, voltage feedback was added. The complete inverter circuit with feedback had a high parts count and used some circuit design considerations not usually found in a student's repertoire. For each project, simulations, measurements, and comparisons between them were required. Scheduled lab time allocated for the project was 12 hours.

Example Laboratory Circuits

Two example circuits are described. One is the LT1172-based 5V-to-12V boost converter and the other is the most recent semester project, the DC-to-AC inverter.

The schematic of the LT1172 boost circuit is shown in Fig. 1 and a layout is shown in Fig. 2. The load resistor is not shown, but it is connected at the terminal block. The circuit was taken from an example included with LTSpice. The LT1172 is very versatile and can be used in any single-switch converter topology having a grounded emitter [Linear, 5]. The LT1172 has an internal BJT switch with its collector connected to the SW pin and emitter connected through a current sensing resistor to ground. The converter output voltage at the terminal block is sensed at the FB pin through resistor divider R2-R3. This provides voltage feedback and the current feedback is derived from the internal transistor switch current sense resistor. The voltage at the FB pin is compared to an internal voltage reference; so the R2-R3 voltage divider sets the output voltage. Components R1, C2, and C3 control the closed-loop response of the converter. Inductor L1 was wound and tested in a previous lab exercise. The electrolytic capacitors are low-ESR

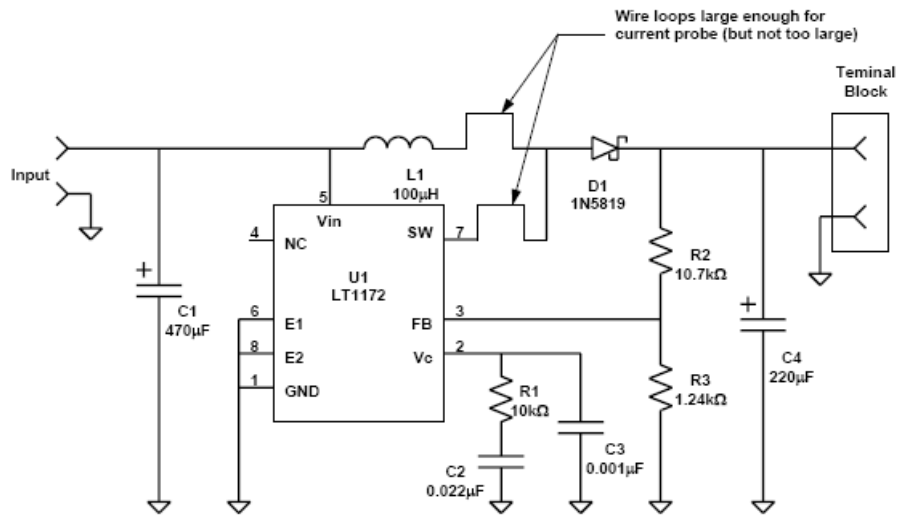


Fig. 1. LT1172 5V-to-12V step-up converter circuit.

aluminum types and the low-value capacitors are ceramic. When students build the circuit, they include some small wire loops as indicated in Fig. 1 to permit current probe measurements.

Simulated and measured results for this circuit compared closely. Steady-state results were obtained for three load resistors: 100Ω, 50Ω, and 20Ω. Simulated and measured efficiencies at the two higher resistances were within 2.5%. Interestingly, the 20Ω load causes switch current limiting for some of the LT1172 ICs, resulting in an unregulated output that drops below 12V. When simulating, a load resistor value slightly below 20Ω caused a similar reduced output, demonstrating that the LT1172 macromodel exhibited generally accurate behavior. RMS ripple measurements were higher in the actual circuit when compared to the simulations due to a larger voltage jump resulting from the equivalent series resistance of capacitor C4.

A block diagram of the pulse-width modulated (PWM) DC-to-AC inverter circuit used for the most recent course

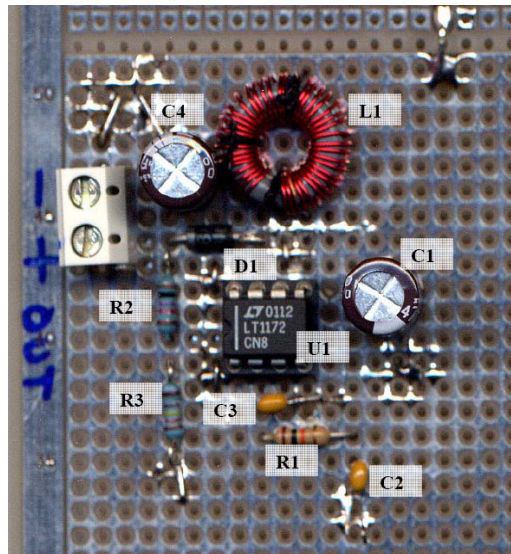


Fig. 2. Step-up converter circuit layout.

project is shown in Fig. 3. The portions of the circuit inside dashed boxes labeled Option 1 and Option 2 were not required, but could be built for extra credit. Although not presented here, students were given schematics with some, but not all, component values specified. They had to use the design specifications to calculate the remaining component values.

The inverter AC output frequency specification was 60 Hz and for the full bridge version, the minimum output voltage specification was 8V peak-to-peak. Other specifications included the DC supply voltages, minimum PWM switching frequency, load resistance, and the attenuation level of the switching frequency at the output. The output voltage was very low for an inverter, but the major objective of the project was for students to see how the inverter functional blocks were implemented. It was pointed out to the students that the inverter they built was similar to a Class-D audio amplifier, in which case the output voltage level was realistic.

One of the important aspects of this design was that the PWM was built in a modular fashion and not integrated into a single component, allowing students to see how PWM waveforms were generated. The pulse generator block was implemented with a TS556 Dual Timer containing two 555-compatible timer circuits [SGS-Thomson, 11]. One timer provided a 95% duty cycle pulse that drove the second timer which was configured as a PWM. The second timer used the pulse to generate a ramp waveform which was compared to a 60 Hz sine wave input to the second timer's reference pin. The PWM output from the second timer connected to an LT1016 comparator with a differential output [Linear, 6]. The half bridge needed only one of the outputs, but a full bridge circuit required complementary versions of the PWM signal to drive two half bridges. LTSpice had a macromodel for a 555 timer, so students could use two of these to model a TS556.

The MOSFETs in each half bridge were driven by a LT1158 Half Bridge Driver that had built-in circuitry to eliminate shoot-through [Linear, 7]. Therefore, students did not have to manipulate the LT1016 comparator complementary outputs to create dead zones to accomplish the same result. The MOSFETs chosen were IRLD014 n-channel parts in a dual-in-line (DIP) package. This part was originally manufactured by International Rectifier but is now manufactured by others [Vishay, 14]. The DIP packages were plugged into sockets on students' circuit boards which allowed for easy replacement in case they were destroyed due to incorrect connections. The output

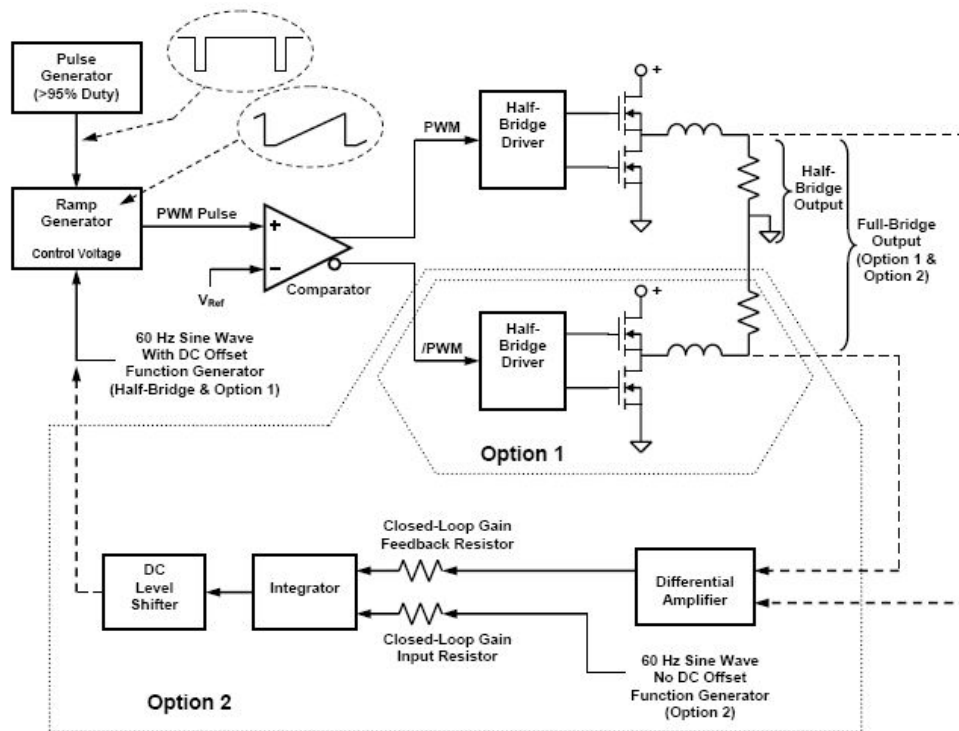


Fig. 3. Inverter block diagram showing optional functional blocks.

filter inductor(s) were designed and built by students to achieve the desired switching frequency attenuation.

The feedback circuit used one dual-amplifier LT1498 IC. One was configured as a differential amplifier that measured the full-bridge output voltage and the other was configured as a differential-input integrator. One input to the integrator was the buffered bridge output from the first amplifier and the other was a 60 Hz sine-wave reference. The integrator time constant was based on the desired closed-loop response, the inverter open-loop gain, and the pole created by the filter inductor. The design procedure for the voltage feedback circuit followed W. Leach's treatment in for a Class-D amplifier [Leach, 3]. Note that the LT1498's rail-to-rail input and output capability was useful with the low-voltage power supplies being used.

The inverter circuit was more complicated than the converters students built in prior exercises or prior projects. All of the student groups completed simulation, construction, and testing of the full-bridge inverter but some did not meet all specifications. Only one group completed the full-bridge circuit with feedback. Simulations proved essential in giving students confidence that they could successfully complete the construction of the circuit and simulated results served as an effective guide when testing and troubleshooting the circuits. The full-bridge circuit with feedback had amplifiers, timers, half-bridge drivers, and a comparator, all of which had built-in LTSpice macromodels. Without these macromodels, the simulation task would have been impossible. Notably, the half-bridge driver macromodel included the shoot-through prevention feature found in the real IC. Incidentally, the LT1158's high side drive capability allows it to drive the floating buck converter MOSFET switches as well.

Laboratory Logistical Concerns

There are several logistical concerns related to the laboratory portion of the Switching Power Supplies course. Dealing with these issues effectively leads to a more efficient course.

The student teams purchased a parts kit with the necessary circuit components having a cost ranging from \$60 to \$90, depending on the semester project. Due to the developmental nature of the course itself and the variable nature of the project, a breadboard rather than a pre-designed circuit board was used. The lab circuits were built on a model 8007 solder-type breadboard available from Vector [Vector, 13]. This breadboard costs about \$27 and is the most expensive single component in the parts kit. This breadboard has a ground plane on top with through holes leading to a pad-per-hole on the bottom. It can be used successfully for circuits operating above 100 MHz depending on construction technique.

To date, the parts kits were assembled by the course instructor, which was time consuming and carried a significant initial cost prior to reimbursement by students. Parts were selected and purchased in advance of the semester based on projected enrollment. This meant that the semester project had to be specified and designed to the point where critical components could be ordered prior to the semester.

The standard laboratory exercises were usually completed within the allocated lab periods, but occasionally students needed more time. In that case access was granted outside scheduled times on an as-needed basis. The semester project usually required more time than students anticipated, requiring extra lab access hours.

Not all students were equally adept at laying out, assembling, testing, and troubleshooting circuits. Most students with engineering technology backgrounds did better in this regard than those with engineering backgrounds. Presumably this was due to the greater number of hours engineering technology students spent in the lab during their undergraduate educations. This observation led to creation of an orientation lab period at the beginning of the semester to instruct students on soldering and assembly techniques and to familiarize them with the lab test equipment.

CONCLUSION

The Switching Power Supplies course laboratory described here was designed quickly and required no additional expenditures by the ECET department to configure the laboratory. Basic equipment found in any electronics laboratory was used. The main exception is that a good impedance meter is required, which the department already had. The current probes mentioned were very beneficial, but not required.

The LTSpice simulator was free of charge and was more than accurate enough to provide the desired result of simulations closely-coupled to experimental results. Having good built-in macromodels eliminated the need for students to design them. LTSpice is an essential part of the course and its flexibility makes it a compelling choice for application-focused courses such as this.

After some consideration, the laboratory equipment could be improved by taking the following measures. Besides adding the current probes mentioned above, perhaps the next most useful improvement would be using an oscilloscope with four channels. Another key improvement would be a higher-capacity DC power supply, reducing the incidences of current limiting that can occur with even the low-power circuits described here. Also, obtaining inexpensive AC-AC wall adapters would permit implementing some low-power AC-DC circuits in the lab. Finally, designing a custom circuit board would allow the circuits that do not change from one semester to the next to be etched on the board, which would result in easier construction for the students. The board would also have a large breadboard area to accommodate the different projects from one semester to the next. Of course, most new parts are being manufactured in surface-mount packages which may require the assembly aspect of the laboratory course to be changed to support this eventuality.

In general, the Switching Power Supplies course laboratory component is demanding of the students and instructor. The logistical issues have been addressed, but not always optimally. Comments from students varied but almost all appreciated the practical nature of the laboratory exercises. Some mentioned the value of comparing simulations and real circuits. Regarding time commitments, students estimated spending between 2 to 10 hours per week on the lab portion of the course with the average at about 5 hours.

Finally, the parts kit issue is always troublesome for lab courses with variable projects. Perhaps the best solution is for the department to manage the acquisition and creation of the kits with close cooperation by the instructor.

REFERENCES

- [1] S. Ang, "A Practice-Oriented Course in Switching Converters," *IEEE Transactions on Education*, vol. 39, no. 1, Institute of Electrical and Electronic Engineers, 1996, pg. 14.
- [2] P. Krein, *Elements of Power Electronics*, Oxford University Press, New York, 1998.
- [3] W. M. Leach, *Introduction to Electroacoustics and Audio Amplifier Design*, 2ed, Kendall/Hunt, Dubuque, IA, 2001
- [4] Linear Technology, Inc. (2008). *Design Simulation and Device Models* [Online]. Available: <http://www.linear.com/designtools/software/>
- [5] Linear Technology, Inc (2008). *LT1170/LT1171/LT1172 100kHz, 5A, 2.5A and 1.25A High Efficiency Switching Regulators* [Online]. Available: <http://www.linear.com/pc/downloadDocument.do?navId=H0,C1,C1003,C1042,C1031,C1061,P1317,D1814>
- [6] Linear Technology, Inc (2008). *LT1016 UltraFast Precision 10ns Comparator* [Online]. Available: <http://www.linear.com/pc/downloadDocument.do?navId=H0,C1,C1154,C1004,C1012,P1225,D2649>
- [7] Linear Technology, Inc (2008). *LT1158 Half-Bridge N-Channel Power MOSFET Driver* [Online]. Available: <http://www.linear.com/pc/downloadDocument.do?navId=H0,C1,C1003,C1142,C1114,P1464,D2064>
- [8] Linear Technology, Inc (2008). *LT1498 10MHz, 6V/us, dual/Quad Rail-to-Rail Input and Output Precision C-Load Op Amps* [Online]. Available: <http://www.linear.com/pc/productDetail.jsp?navId=H0,C1,C1154,C1009,C1021,P1532>
- [9] Magnetics, Inc. (2008). *Powdered Cores Design Manual and Catalog* [Online]. Available: <http://www.mag-inc.com/powder/catalog.asp>
- [10] National Semiconductor, Inc. (2008). *Power Management* [Online]. Available: <http://www.national.com/analog/power>
- [11] SGS-Thomson Microelectronics. (2008). *TS556 Low-Power Dual CMOS Timers* [Online]. Available: <http://www.st.com/stonline/products/literature/ds/4078.pdf>
- [12] S. Shirsavar, "Teaching Practical Design of Switch-Mode Power Supplies," *IEEE Transactions on Education*, vol. 47, no. 4, Institute of Electrical and Electronic Engineers, 2004, pg. 467.
- [13] Vector Electronics & Technology, Inc. (2008), *Vectorbord Circbord Part No.: 8007* [Online]. Available: <http://www.vectorelect.com/Product/Circbord/8007.htm>

- [14] Vishay Intertechnology, Inc. (2008). *IRLD014, SiHLD014 Power MOSFET* [Online]. Available: <http://www.vishay.com/docs/91307/91307.pdf>

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