ASEE AMERICAN SOCIETY FOR ENGINEERING EDUCATION

2017 Pacific Southwest Section
Meeting: Tempe, Arizona Apr 20 Paper ID #20681

Teaching the Hands-on Magnetic Design Laboratory Course: Experience and Lessons Learned

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Abstract

One important concept in electrical engineering that is rarely being taught at an undergraduate level is magnetic component design. The concept involves abstract analysis of magnetic flux and the physical structure of the magnetic components such as inductor and transformer. To address this issue, the Electrical Engineering department at Cal Poly State University in San Luis Obispo introduced a new undergraduate course in magnetic design with laboratory component where students learn practical magnetic design, build and test their own inductors and transformer. This paper focuses on the laboratory experiments developed for the course. Expected student learning outcomes and laboratory experiments and hardware modules to achieve the outcomes will be detailed in this paper. Challenges and lessons learned in teaching the course will also be presented.

Introduction

Electrical engineering is a broad field of engineering which encompasses many areas such as communication, controls, electronics, computers, electromagnetics, and power. Within the power area there are sub-disciplines which are typically categorized into the traditional power systems, power electronics, electric machines, and renewable energy. In California, Cal Poly State University is among a few universities that offers power concentration within the electrical engineering department. In addition to requiring all electrical engineering students to take the electric machines class, the department offers many technical elective courses in power systems, power electronics, renewable energy, and machines.

One sub-area of power that has recently undergone major improvements is power electronics. Power electronics is enabling technology that allows billions of kilo-watts of electrical power to be re-processed every day while providing significant energy savings[1]. For this reason, the interest among electrical engineering students at Cal Poly State University on power electronics has grown steadily in the last decade as indicated by the increase on enrollment in the power electronic courses[2] which include Introduction to Power Electronics (EE410), Advanced Power Electronics (EE411), DC-DC Converter Design (EE527), and Introduction Magnetic Design (EE433). However, among these courses the one particular topic that has been known to be one skill or knowledge that electrical engineering students in general do not possess[4] is the magnetic component design. Electrical engineering students are so accustomed to using commercially available inductors or transformers whenever they need to use them in their projects. Often times this approach is not practical as commercially available magnetic components are limited in their standard values. Furthermore, power semiconductor companies many times require their new electrical engineers to have the basic magnetic design skill enough to design and build their own magnetic components for their prototype products. This in turn will reduce company’s time to production as well as minimize prototyping cost. To address this issue, Cal Poly State University recently developed a magnetic design course offered as a technical elective for electrical engineering students. The course has two components: lecture and laboratory. This paper details the five laboratory experiments that have been developed for the lab portion of the course. Laboratory hardware modules and their expected student learning outcomes as well as lessons learned in developing and teaching the lab course will also be presented.

The Course

Magnetic components have been used extensively in the practice of electrical engineering, yet as previously mentioned courses that deal with magnetic component design and construction are not typically offered in universities in the U.S. The coverage of magnetic components is usually limited to their functionalities in circuits. As modern circuits become more advanced and complex, the expectation from industry for electrical engineering graduates becomes higher. For example, those graduates who are going into power semiconductor industries are now expected to know some design skill on laminated iron-core inductors as they are widely used in the power electronics industry[2].

The issue of lack of "magneticians" has in fact long been recognized by industrial group[3] and has encouraged several universities in the US to introduce more applied magnetic design into their undergraduate curricula[4]. In attempt to address this issue, the Education Committee of the IEEE Magnetics Society has debated the question of whether to ask for a minimum competency in magnetic design for accreditation[5], but fell short of actually taking such a step. At Cal Poly State University in San Luis Obispo we have taken the position that magnetic design is a critical design skill set to our electrical engineering graduates. Thus, in 2009 we revised our existing magnetic course and reintroduced the course to enhance students' practical design and construction skills in magnetic components. Below is the catalog description of the course[6].

EE 433 Introduction to Magnetic Design
Design of magnetic components. Fundamentals of magnetics, magnetic cores, design of power transformer, three-phase transformer, dc inductor, ac inductors, dc-dc converter transformer design, actuators. Use of commercially available software. 3 lectures, 1 laboratory.

As shown in the above course description, students taking the course must enroll in the laboratory portion of the course. The lab course entails weekly three-hour lab time where students conduct experiments involving design calculation, computer simulation, hardware verification and test. The software used for the simulation is the LTSpice which is available for free from Linear Technology[7].

Five new laboratory experiments were developed to enforce students' understanding of the design, construction, and testing of inductor and transformer. The experiments are listed below:

- Experiment #1: Rudimentary Short Rise-Time Dynamical Reluctance Basics
- Experiment #2: Characterizing Core Material (B-H)
- Experiment #3: Inductor Design
- Experiment #4: Transformer Design
- Experiment #5: Flyback Transformer Design

The Lab Experiments

Experiment #1

The main learning objective of the first experiment is for students to be able to calculate the energy stored in an inductor. Students perform inductance calculation and its corresponding energy. They build their own basic inductor from loops of wire, culminating in an air-core inductor as well as the effects of adding a magnetic core. To study the energy stored in the inductor, students use their hand-made inductor to launch a mass (a piece of steel) placed inside the air core of the inductor. Prior to building the inductor, students must simulate the circuit along with their designed inductor to verify their energy calculation. Students then conduct the hardware test by using a premade energy transfer circuit as shown in Fig. 1.

Figure 1. Energy transfer circuit used for Experiment #1

Experiment #2

The learning objective of this experiment is for students to demonstrate and measure a magnetic core's hysteresis loop, saturation, and permeability. Understanding the loop of a magnetic core is essential in the design process of magnetic components since it indicates electrical constraints of the core when used for a magnetic component. As in experiment #1, students must use LTSpice computer simulation to verify theirdesign prior to conducting their hardware test. Fig. 2 shows the pre-made circuit module for students to use to study the hysteresis loop.

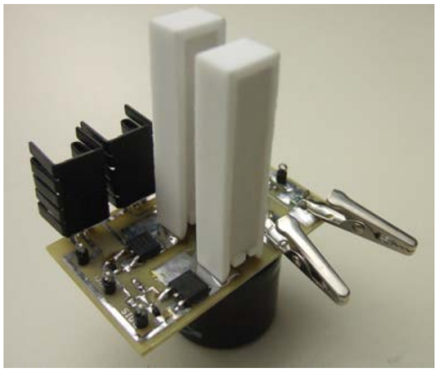

Figure 2. Test circuit for Experiment #2

Experiment #3

This experiment has the learning objective that students will be able to practice the design of a high frequency power inductor, verify their design using LTSpice simulation, construct and then test their design. Students investigate three candidate cores and then choose one based on given design constraints and trade-offs to consider. Hardware test follows after selecting the core. First, they build their inductor and then measure the inductance to verify against their desired design value. Once this process is completed, then they will use their inductor in a pre-made converter module as shown in Fig. 3. Students then observe several waveforms under varying operating conditions of the converter to verify their design.

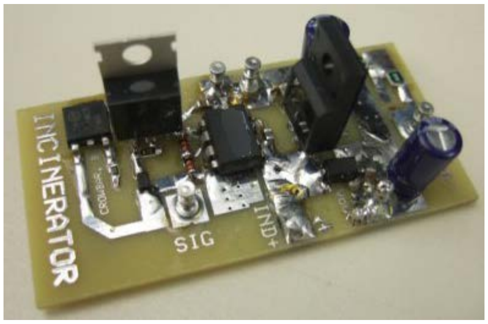

Figure 3. Buck converter test circuit for Experiment #3

Experiment #4

Experiment #4 entails the design, simulation, and construction of a transformer. The format and procedure for the lab is similar to that of Experiment #3 except the learning objective here is for students to apply design equations for transformer, simulate their design, and perform hardware testing to test their transformer. The pre-made circuit module that students will have to use for the experiment is shown in Figure 4.

Figure 4. Inductor current hardware measurement

Experiment #5

The learning objective of experiment #5 is for students to have the ability to apply flyback transformer design equations to construct, test, and analyze their design using a pre-made flyback circuit module. In this experiment, students have the freedom to choose any magnetic core as long as their final test results pass the given design goals. If any of the design goals is not satisfied, then they will have to redo the design until the design fulfills all requirements. Figure 5 displays the pre-made module for the experiment.

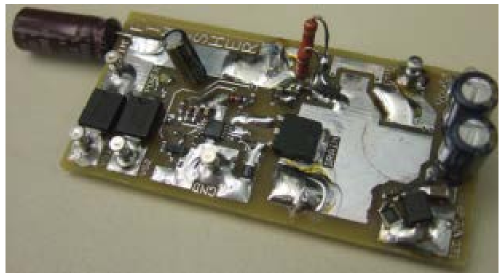

Figure 5. Inductor current hardware measurement

Course Assessments

For course assessment in the laboratory portion of the course, in addition to laboratory report submission required for every lab experiment, students are asked to respond to the following survey questions by the end of the course:

	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
You can perform basic inductor design	○	○	○	○	○
You can perform basic transformer design	○	○	○	○	○
You can model and simulate non-linear magnetic core	○	○	○	○	○
You can build, measure, and test inductor	○	○	○	○	○
You can build, measure, and test transformer	○	○	○	○	○
You can operate lab instrument for inductance measurement	○	○	○	○	○
The lab course complements the materials covered in the lecture	○	○	○	○	○

The survey was conducted in 2008, 2010, and 2013 whose results for each question are shown in Fig. 7. The results indicate that in general the lab course has been successful in enhancing students' knowledge and skills in magnetic design and constructions. The majority of students believe they will be able to build inductors and transformers after completing the lab course. Students also experience the lab to complement well the materials from the lecture part of the course. The results from survey questions #3, #4, and #5 also indicate that there are three items that may be improved. Plans and actions for addressing these items are currently being conducted. For example, coverage and assignment on modeling of non-linear magnetic core will be expanded in the lecture portion to address the issue related to question #3.

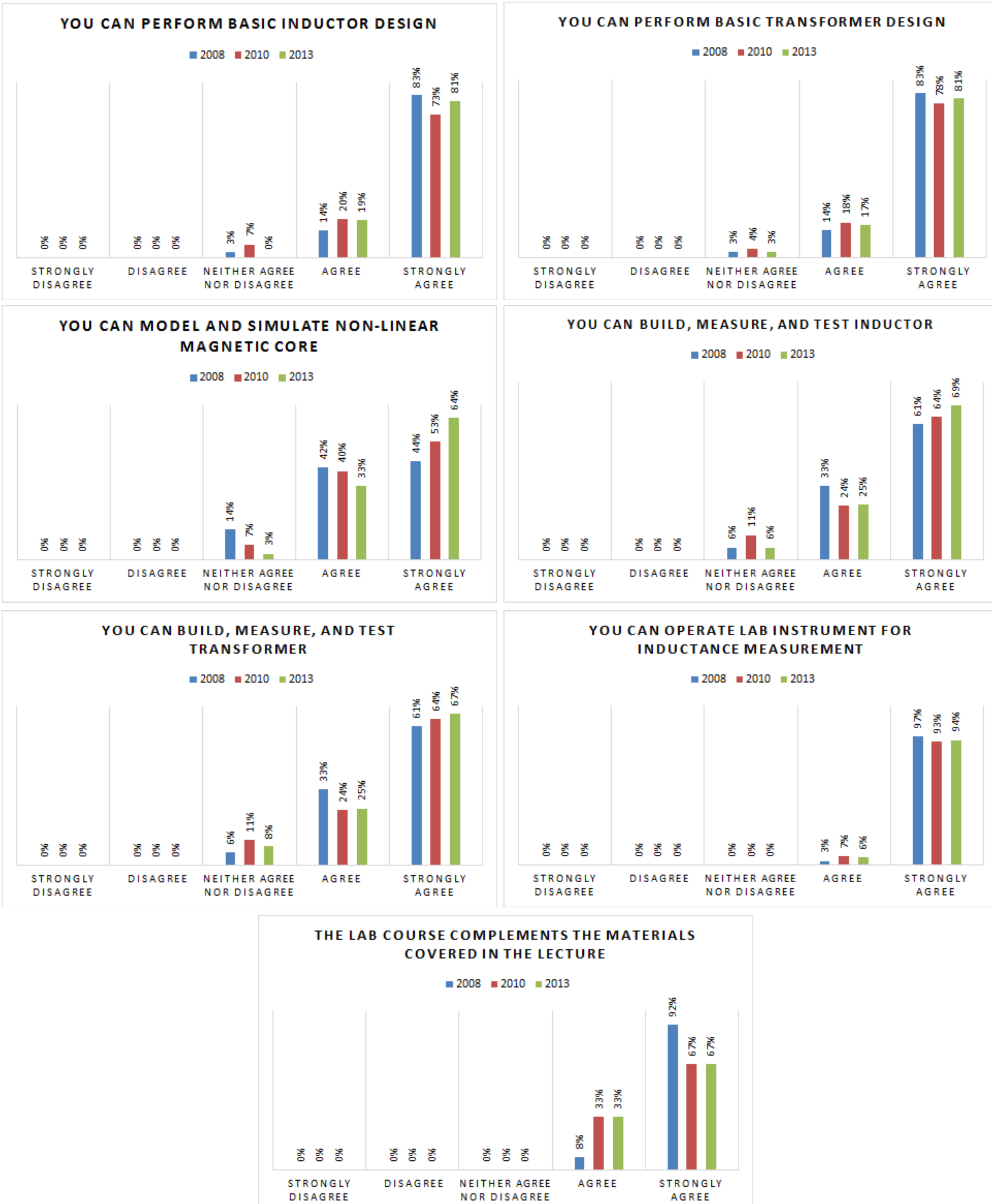

Figure 5. Survey results for the lab course assessment

Experience, Lessons Learned and Challenges

As previously explained, each experiment requires students to perform computer simulation of their design. To minimize both the cost and learning time associated with the software used for the simulation, LTSpice was chosen for the lab. The LTSpice is available for free; thus, there is no cost associated with the software. LTSpice is also relatively simple to learn and use.

As in any other labs, having a well-organized lab manual with clear instructions on the steps used for each experiment is important. However, the real challenge in teaching the lab is in terms of the logistics for the hardware used in the lab course. In this lab at its present format, students are provided the materials such as magnetic cores, bobbins, clips, magnet wires and others required to build the magnetic components. This takes careful planning prior to teaching the lab course since it may take a long lead time to acquire some of the materials. There is also cost associated with these materials which is minimized by requiring students to disassemble their designed magnetic components once they complete their experiments. Another big challenge is the time it took to build the hardware modules as test circuits for students to verify their magnetic components. Moreover, these test boards for all experiments may cost up to $3000. At present, the boards were designed so that students can test their magnetic components by soldering onto these boards. This may create the problem of long waiting time in running the experiments if there are not enough soldering stations for students to use. Another problem is the risk of students damaging the test boards due to the soldering connections that students have solder and unsolder to connect their magnetic components. The later problem may be minimized by redesigning the boards to allow different component connection other than the soldering type.

Conclusion

This paper presents the experience and lesson learned from teaching the lab course on magnetic design. The course was developed to address the issue of the lack of magnetic design skills among electrical engineering graduates. Five experiments in the course were described in this paper along with their learning objectives and hardware components. Lessons learned from teaching the course emphasize the challenges in teaching the course in terms of course preparation and running the experiments. Survey results conducted by students indicate the effectiveness of the lab course in improving students' knowledge and skills in magnetic component design. Improvements on the lab course based on the survey results are currently being conducted. Lastly, the lab manuals for these experiments will be made available on line so other universities who are interested in establishing a similar course may make use of the already developed materials.

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