Development of a Small, Robust, and Portable Circuits Training System for an Introductory Course in DC Electrical Circuits

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Abstract

Realizing a gap in student's ability to make connections between theoretical concepts and applied methods in an introductory DC Electric circuits course we have developed a small, robust, and portable circuits training system. The designed system met the requirements of being self-contained, simple for student operation, robust, portable, and economically viable. In this paper we describe the details of integration of our system into an existing introductory DC Electric circuits course and additionally, details of the planned study including implementation and assessment are discussed.

Keywords

Active learning, DC Circuit Analysis, Portable Lab, Kinesthetic Learning

Introduction

At Arkansas Tech University (ATU) Electric Circuits 1 is an introductory engineering course that teaches students electrical concepts utilizing direct-current (DC) circuit analysis and basic electrical devices. This course is designed to provide a foundation for a sequence of courses in alternating current (AC) circuits, electronics, electrical machines, and engineering design for electrical engineering students. In addition to the electrical engineering majors, mechanical engineering, physics, and engineering physics students are also required to successfully complete this course. In order for a student to enroll in the course he/she must be concurrently enrolled in Differential Equations or have successfully completed the class with a passing grade. Additionally, although not required, most of the Mechanical Engineering, Physics, and Engineering Physics majors have already been exposed to some of the basic concepts in DC circuits through their experience taking General Physics 2 (this is the Calculus based Electricity/Magnetism physics course). This course also has a traditional lab component where the students perform 1-2 circuit activities. With the exception of the students who have previously taken General Physics 2 there has been little to no formal exposure to electrical circuits. Most of the courses in the students' curriculum have, at this point, been heavily theoretical in nature. A major shortcoming identified with the Electric Circuits 1 course is that upon completion, the majority of students lack a thorough knowledge of the concepts being taught. It is believed that this is a result of the students' failure to effectively make connections between theoretical concepts and practical applications. This conceptual gap in student's electric circuits knowledge remains until after completion of several lab classes and has the effect of increasing the difficulty in grasping more advanced electrical concepts.

Background and Methods

Ambrose et al[1] has shown that students are adept at learning disparate basic physical laws and theorems yet unable to organize and integrate them into a complete understanding of a system. For example, in circuits analysis, students may be able to recite Ohm's and Kirchhoff's laws but are unable to apply them in a circuit analysis exercise. The traditional approach to addressing the gap between theory and practice is to provide the students with separate circuits lab courses. This is a reasonable solution given the plethora of research demonstrating that in-class instruction, when supplemented with experiential learning is significantly more effective than lectures alone.[2-6] Ideally, lab and lecture content would be synchronized such that the students would be introduced to a theoretical topic in class and then have that topic reinforced with an appropriate lab exercise prior to introduction of a new topic. However, this traditional approach generally has short comings because synchronization between the lecture topics and the lab activities is not maintained due to the difficulty in implementation. When this occurs the reinforcement benefits of the lab activity can be significantly reduced. Misalignment between course topics and lab exercises occur most frequently when the lab instructor and course lecturer are different resulting in an inherent lack of coordination between the two instructors. Finally, the traditional lab approach is resource intensive requiring lab space, specialized test equipment, and personnel dedicated to lab instruction and maintenance. Furthermore, if the lecture class is significantly large it could require multiple lab sections to accommodate all of the students.

In the case of ATU, the problems detailed with the traditional lab approach are exacerbated by the fact that students are not offered a lab course that is concurrent with Electric Circuits 1. Instead, they are required to take the associated Electric Circuits Lab the semester following the lecture course. Furthermore, at ATU, budget management has resulted in an effort to increase class sizes as a way to operate in a more cost effective manner. As a result, Electric Circuits 1 typically has an enrollment of between 60-70 students for the Fall semester and 30-40 students for the Spring semester. The dedicated lab space can accommodate only 24 students with two students per station which would require three lab sections for the Fall and two for the spring semester. Furthermore, the lab space is at a premium since it is a multiuse space (this space is shared with Electronics, Communication Systems, and Senior Design). Finally, with year-to-year enrollment growth projections in engineering, these problems will continue into the foreseeable future.

In an effort to address the conceptual gap in electrical engineering learning within the framework of the resource limitations described above, Arkansas Tech University set out to institute a laboratory education method more closely integrated with the classroom lectures. Several requirements were developed for implementation of the new program.

Lab exercises would be coupled with the university’s existing Electrical Circuits 1 course and would consist of simple and focused experiments designed to reinforce the current classroom theoretical concepts. To provide the needed synchronization between classroom and laboratory exercises and provide immediate reinforcement, the laboratory exercises would be performed following the lecture during on the student’s personal time (i.e. not in class and not in a formally scheduled lab period). The laboratory exercises are being strategically written such that a student could complete the activity in less than an hour. This implementation would preclude the use of a traditional 3 hour per week lab class.

The concept of introducing a "mini-laboratory" in a manner that precludes the use of the traditional university laboratory facilities presented its own set of unique challenges. In reality what would have to be employed would be a small, portable lab station that could be utilized by all students in the class at some location other than a classroom or laboratory setting. To implement this approach, several key attributes for the portable lab system were identified. First, it must be self-contained allowing the student to perform all of the experiments without access to the Electric Circuits Laboratory, specialized test equipment and dedicated software. Secondly, the system had to be simple so as to allow a student with little or no training to easily master its use within a brief period (i.e. 15 minutes). Only features needed for accomplishment of the experimental exercises need to be included in its operational repertoire. Thirdly, the system must be easily portable and exceptionally robust in order to be carried by the students and withstand their day-to-day wear and tear. Finally, the chosen system must be economically viable since, since during the proof of concept phase the University will fund 66 of the units with its implementation it would be student purchased.

Selection of the "Mini-Lab" hardware began with a product search of existing off-the-shelf equipment. Several companies have developed what are generally designated as circuit trainer boards and these were reviewed for their individual capabilities and adherence to our criteria.

The "Analog Discovery" offered by Digilent consists of a USB powered device that allows a student to measure and analyze mixed signal circuits. The device incorporates a 2-channel oscilloscope, signal generator, spectrum analyzer, voltmeter, and several other features. This system was very attractive; however, it had issues that precluded use for our specific application. The system cost was $99 for students[7] and in order to operate it a computer was required to run the dedicated Digilent Waveform software. Furthermore, this system didn't include a breadboard and hook-up wires and was not necessarily physically robust in its design. Finally, the system had numerous features that were not required as the "Mini-Lab" was envisioned. These would lead to a steep learning curve for students since operation of the dedicated software would need to be learned and most have never worked with electronic circuits or test equipment before.

The RSR/Virginia Tech A & D board is another attractive product that was reviewed. This board, designed by Virginia Tech and RSR Electronics, contains 2 breadboards, 3 DC power supplies, a function generator, a digital clock, digital pulsers, digital buffered switches and digital logic probes. It sells to Virginia Tech students for approximately $60 each. This price does not include hook up wire or a carrying case. The main disqualifier for our implementation was the system's lack of simplicity. Additionally, as with the Digilent Analog Explorer, the A&D Andy Board contained many features (namely the function generator and the digital electronics) that aren't required for the DC circuits course "Mini-Lab".

Another approach considered was to adopt a software solution whereby the students could build the circuits virtually and then have the software simulate the circuit's behavior. There are many free circuit simulations programs available that would sufficiently meet the objectives of the study. This approach was not selected for initial evaluation because of the desire to isolate the study variables in order to evaluate the educational benefits of hand-on applied methods. Additionally, there was a concern that introduction of circuit simulation tools at the beginning of the students' exposure to circuit analysis might become a crutch for solving problems.

Since the product research efforts failed to identify a hardware system that met our designated requirements of a being self-contained, simple, robust, portable, and inexpensive, a design effort was initiated resulting in the prototype shown in Figure 1. The system consists of a proto-board attached to a plastic case that encloses the associated electronics. The electronics provide a fixed 12VDC supply and a 1.25V – 10.5VDC variable supply capable of providing a total current of 500mA. The power forms are fuse protected (to 500mA) and controlled by a switch and a potentiometer. A tri-color LED is used as an indicator light and glows white when the electronics are functioning properly and red when the fuse is blown. DC power (either fixed or variable) is supplied to the proto-board using proto wires connected to spring connectors. The system has a small footprint 7’’× 5’’ ×2’’ and is lightweight (0.8 lbs) and portable. The complete system including a digital multi-meter for voltage, current, and resistance measurements, a set of hook up wires and a carrying case cost approximately $60 USD. The system was designed by university staff and wired/assembled by undergraduate students. Openings in the plastic enclosure were machined by a benchtop CNC mill which was programmed and operated by ATU undergraduate students.

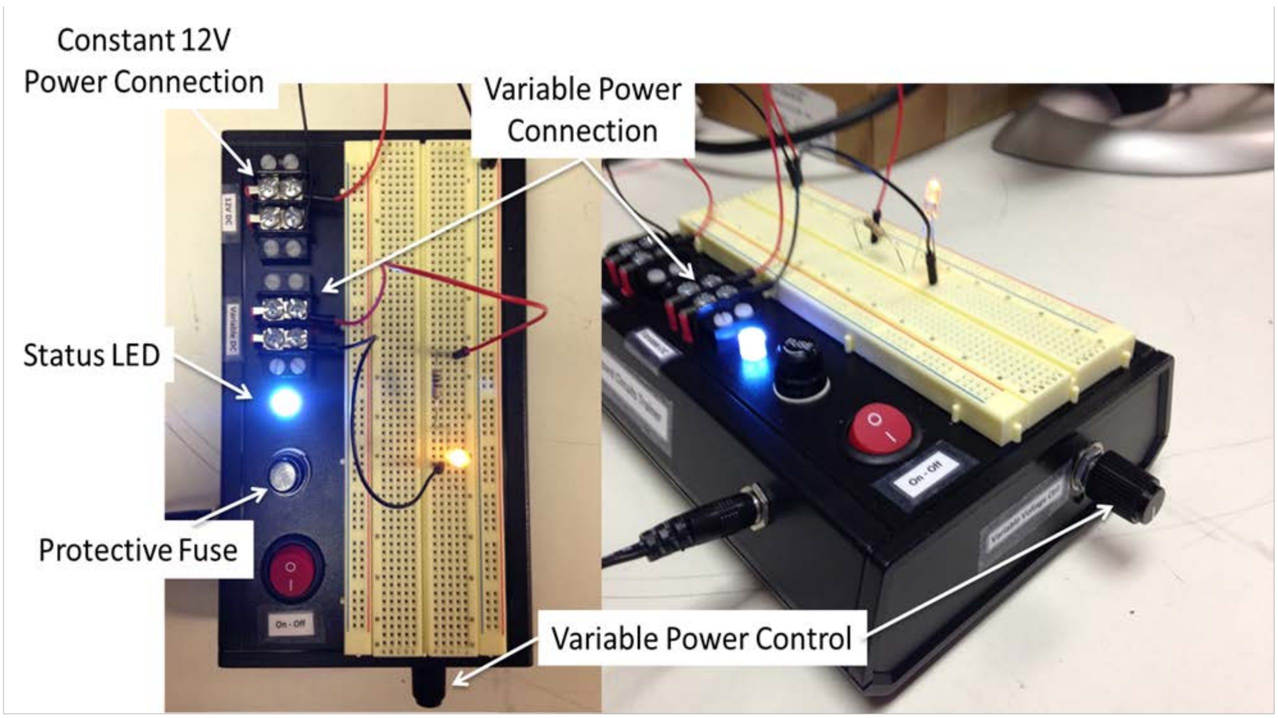

Figure 1 Image of the working prototype of the mini-lab system. The system is designed to output either a constant 12-VDC or a variable 0-10.5-VDC. It is also equipped with a protective 1-Amp fuse.

Procedures - Mini-Laboratory Exercises

The Mini-Laboratory will be integrated into the curriculum in the Fall 2015 semester. To measure its effects on student electric circuits knowledge, a structured evaluation program will be utilized. The students will be separated into two groups such that each group has an equivalent average overall GPA and an identical number of electrical engineering, mechanical engineering, and physics majors. One group will perform laboratory exercises utilizing the mini-lab hardware described above. The second group (i.e. the control group) will not utilize the mini-lab or its associated exercises but instead will participate in the traditional course experience. The Arkansas Tech University Institutional Review Board has reviewed and approved the experimental protocol.

The mini-lab activities are specifically designed to address the ATU course objectives for Electric Circuits 1. These course objectives are:

1. Define the basic physical quantities of circuit elements.
2. Demonstrate the ability to simplify complex circuits.
3. Solve problems using circuit laws and theorems.
4. Solve simple 1^{st} and 2^{nd} order circuits.
5. Design simple circuits.

The "mini-lab" system is versatile enough to address each of the course objectives except number 4. The current limitation with the system is an inability to perform the necessary transient analysis needed to explore simple 1^{st} and 2^{nd} order circuits. In addition to addressing the above course objectives, the mini-lab activities are also chronologically arranged to synchronize with the presentation of lecture material. Employment of the mini-lab system offers flexibility allowing the instructor to assign lab activities based on lecture progress and alleviates the rigidity inherent in the traditional dedicated lab course.

Below is a list of the mini-lab activities:

1. Title: INTRODUCTION TO MINILAB
   Description: A brief primer on how to construct basic circuits including using the minilab system and an introduction to data plotting with excel.

2. Title: OHM'S LAW
   Description: A brief introduction on use of a multimeter as well as an activity to verify Ohm's Law.
   Course Objective Relevancy: Define the basic physical quantities of circuit elements, Solve problems using circuit laws and theorems

3. Title: KIRCHHOFF'S VOLTAGE LAW
   Description: An activity that demonstrates Kirchhoff's voltage law and its use in solving circuit problems.
   Course Objective Relevancy: Demonstrate the ability to simplify complex circuits, Solve problems using circuit laws and theorems

4. Title: KIRCHHOFF'S CURRENT LAW
   Description: An activity that demonstrates Kirchhoff's current law and its use in solving circuit problems.
   Course Objective Relevancy: Demonstrate the ability to simplify complex circuits, Solve problems using circuit laws and theorems

5. Title: NODAL ANALYSIS
   Description: Students will make measurements on a circuit and compare them to those calculated using nodal analysis.
   Course Objective Relevancy: Define the basic physical quantities of circuit elements, Solve problems using circuit laws and theorems

6. Title: MESH ANALYSIS
   Description: Students will make measurements on a circuit and compare them to those calculated using mesh analysis.
   Course Objective Relevancy: Define the basic physical quantities of circuit elements, Solve problems using circuit laws and theorems,

7. Title: THEVENIN and NORTON THEOREM
   Description: Students will construct a circuit network followed by measuring of relevant electrical parameters. These measurements will then be applied to calculate, construct, and validate the Thevenin equivalent network.
   Course Objective Relevancy: Demonstrate the ability to simplify complex circuits, Solve problems using circuit laws and theorems

8. Title: OPERATIONAL AMPLIFIER CIRCUIT DESIGN
   Description: This project will introduce the student to basic circuit designs for single supply operational amplifier circuits. The students will then build and test their design to validate the circuit's performance.
   Course Objective Relevancy: Solve problems using circuit laws and theorems, Design simple operational amplifier circuits

Associated with each activity is a short write-up with instructions for performing the lab. In addition, a brief video will be available to the students to supplement the written exercise instructions. To motivate the students to actually perform the mini-lab activities each student will turn in a brief lab report for each activity that will be a significant portion of their overall course grade.

Assessment

This study has been designed to test the efficacy of mini-labs integrated into the Electric Circuits course with the aim of enhancing students' ability to develop a comprehensive understanding of circuits sufficient to enable application in circuit analysis and design. Cognitive learning occurs at several levels as indicated in the revised Bloom's taxonomy model[8]. At the lowest levels, students are able to remember and understand the basic circuit laws and theorems without the ability to integrate them with circuit analysis and design. To assess these different levels of understanding an exam will be administered at the end of the semester to both the evaluation and control groups. The exam will be composed of two categories of questions. The first category will test the students' ability to remember and understand circuit laws and theorems (addressing the lower level of Bloom's cognitive processes dimension) while the second category will assess the students' analysis and design abilities (addressing the higher level of Bloom's cognitive processes dimension). An example of a question from the first category to test basic knowledge of circuit laws and theorems would be the following:

> **Question:** Given a linear graph of current vs voltage, find the associated resistance.
>
> **Solution:** In order to solve this problem the student must recall Ohm's law and recognize that the slope of the line of current vs voltage is the reciprocal of the resistance.

The second category of exam questions which evaluate the higher level cognitive processes will require the students to integrate the information from several topics to analyze or design circuits. For example, a representative question to test a student's understanding and application of circuit principals and not just "applying a formula" would be:

> **Question:** Design a voltage divider circuit such that, when a load resistor of similar magnitude to the sum of the resistors comprising the voltage divider is placed into the circuit, the output voltage of the loaded voltage divider circuit is the same as that of the original unloaded circuit.
>
> **Solution:** A solution to this problem would be to place a voltage follower op-amp circuit between the voltage divider output and the load resistor. This requires the student to not only understand circuit theory but also generate a system's model that requires interfacing individual circuits to generate a specified output.

The assessment results from the first category of questions will be compared between the two study groups. If the groups are evenly matched, no statistically significant difference in the assessment results would exist. The assessment results from the second category of questions will then undergo evaluation to determine if a statistically significant improvement exists between the two study groups. If after comparing study groups, there is a statistically significant difference in the first category assessment scores these results will be used to normalize the scores from the second category.

Summary and Conclusions

In conclusion, a small, portable system has been developed to allow students to perform simple DC circuit lab exercises outside of the classroom and without the need of a dedicated lab facility. The system was designed with a fixed and a variable power supply integrated with a proto-board for circuit construction. Over the course of the Fall 2015 semester, students will perform 8 separate lab exercises that will coincide with their respective topics in the lecture. To measure the effect of implementing the mini-lab system, an assessment exam will be administered at the end of the semester to both a control group and evaluation group of students.

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