Development of Simulation Models for Power Converters – Undergraduate Research Experience

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Abstract – The value of early exposure of engineering undergraduates to research has drawn much attention over the past decade, and a wide array of creative options have been explored. This paper discusses the process and challenges of guiding a group of engineering undergraduate seniors through a research project that holds the potential of exposure to realistic engineering problems, and a motivation for students to pursue advanced studies.

Index Terms – Undergraduate research, power electronics.

1. Introduction

The merits of involving engineering undergraduates in research have been widely discussed in engineering journals. It has been suggested that such an initiative may help the student become more passionate about the subject, create appreciation for research process and practice, improve problem-solving skills or even serve as motivation for further education in graduate school[1-3]. Furthermore, it allows advanced students an opportunity to be exposed to challenging and realistic engineering problems they may encounter in post graduation work. In some cases, the students participate directly in a funded research that holds significant benefit to all participants – students, faculty, and the university[4]. The growing recognition of the importance of undergraduate research is underscored by the determination to deliberately embed undergraduate research in the curriculum in some engineering programs, through involving students in innovative design experience[5-6].

The modalities of productively involving less experienced students in meaningful research is however not trivial. This is largely due to the strict requirements of the undergraduate curriculum that often call for heavy course loads. Many students begin to take elective classes in engineering specialty areas when they are in their final year. This leaves little room to engage in research after acquisition of basic knowledge in the relevant courses. Since research by nature tends to impose more demands on time, it is not very attractive to an overburdened undergraduate student without some meaningful incentives.

This paper discusses the process and challenges of guiding a group of engineering undergraduate seniors through a research project that gets them exposed to typical real-life engineering problems. The project is centered on a variety of switching power converter available in the energy conversion environment at Penn State Harrisburg. Students were required to partially dismantle a power electronic converter to enable a closer examination of its construction and operation. They were also required to study the interconnection of components, conduct performance tests, collect data, and develop a detailed computer simulation model for the system. Such model would be adequate for system redesign.

To be successful in this project students need basic knowledge of power electronic circuits, understanding of the design of automatic control systems, familiarity with software modeling tools for electrical network and systems, and a sufficient amount of time within the normal semester. The students involved in this project were in their final year, and were enrolled in their first course in power electronics during the research experience. Most of them had not taken courses in automatic control, but they all had prior exposure to software simulation tools such as PSPICE and some familiarity with MATLAB-SimPowerSystem modeling environment.

Students learned to operate the converter, conduct loading tests and logging of data that would be used for validation of the model. They learned how to collect specification data for modeling in the MATLAB environment, apply strategies for model simplification, and validate simulation models using experimental data.

This paper documents the class experience over two years.

2. Power Electronics Course at Penn State Harrisburg

Table 1 shows the contents of the power electronics course at Penn State Harrisburg. Although the course is a 3.0-credit technical elective some students opt to enroll in an additional 1.0-credit independent study course. The independent study course format presents both students and instructors the opportunity to explore a wide variety of options for enhancing students' understanding of the subject. While the course could be structured as a series of laboratory experiments in power electronic circuits and components, the preference over the last two years has been towards research and modeling studies. This option gives the student far more control of the learning process than occurs in typical laboratory courses.

A meaningful learning experience in power converter analysis, simulation and modeling will only take place if students have the appropriate fundamental background course materials. Critical fundamental subjects includes an introduction to power electronic circuits, familiarity with modeling tools (e.g. PSPICE, MATLAB-SimPowerSystem), and linear feedback control system. The rather restrictive nature of the undergraduate curriculum in many EE programs presents difficulties in moving students through background material ahead of the research exposure. At the earliest most students find it convenient to enroll in either power electronics or control systems course in the first semester of the senior (graduating) year.

It could be observed from Table 1 that preliminary materials that could not be overlooked dominated the first five weeks of the semester. Topics which are more pertinent to newer technology converters are not broached until nearly mid-semester. It becomes obvious that so much of the activities will have to take place concurrently. That is, students will learn converter basics, control system application in converters, develop skills in computer modeling, and integrate all of these in understanding a fairly complex engineering system.

Table 1. Power electronics course syllabus (fall 2003).

WEEK	TOPICS
1.	**(1.1– 2.10) <u>Introduction to the course</u> -** converter classification, switches, modeling using MATLAB - SimPowerSystem. Power Computations – power & energy, L & C, power definitions, power in sinusoidal and non-sinusoidal circuits. **Homework project –**
2.	**(3.1- 3.12) <u>Half-Wave Rectifiers</u> –** R, R-L loads, R-L & L source load, Freewheeling diode, capacitor filter, controlled rectifier, commutation, simulation in MATLAB. **Homework project –**
3.	**(4.1-4.3) <u>Full-Wave Rectifier</u> –** Single-phase full-wave rectifier, controlled full-wave rectifiers. Simulation in MATLAB. **Homework project –**
4.	**(4.4- 4.8)** Three-phase rectifier, Controlled three-phase rectifiers, DC power transmission, commutation. Simulation in MATLAB. **Homework project –** **Exam #1**
5.	**(5.1-5.6) <u>AC-to-AC Converters</u>** – Single-phase AC voltage controller, three-phase voltage controllers, Induction motor speed control, static VAR control. Simulation in MATLAB. **Homework project –**
6.	**(6.1-6.6) <u>DC-to-DC Converters</u>** – Linear voltage regulators, basic switching converter, The Buck converter, The Boost converter, The Buck-Boost converter. Simulation in MATLAB. **Homework project –**
7.	**(6.7-6.11)** The Cuk converter, converter performance, discontinuous current operation, PSPICE modeling. **Homework project –**
8.	**(7.1-7.12) <u>DC Power Supplies</u>** – Transformer models, Converter configurations - Flyback, Forward, Double-Ended Forward, Push-pull, Full/Half bridge DC-DC, Current-Fed. Converter selection. **Homework project –** **Exam #2**
9.	**(8.1-8.8) <u>Inverters</u>** – The Full-Bridge converter, The Square-Wave inverter, Fourier analysis, Harmonic distortion & control, Half-Bridge inverter. Simulation in MATLAB. **Homework project –**
10.	**(8.9-8.16)** Pulse-Width-Modulated output, Harmonics, Simulation of PWM inverters, three-phase inverters, Induction motor speed control. Simulation in MATLAB. **Homework project –**
11.	**(9.1-10.10) <u>Resonant Converters</u>** – Zero-current & Zero-voltage switching, The Series resonant inverter, The Series resonant DC-DC converter. **<u>Drive and Snubber Circuits.</u> Homework project –**
12.	**(*Kissell 10-11) <u>Industrial Electronics</u>** – Overview of input & output devices (sensors, transducers, transmitters, valves, relays, variable frequency drives, stepper and servo motors). **Homework project –** **Exam #3**
13.	**(*Kissell 10-11)** Overview of Programmable Controllers – Features & operation. Basic instruction set, and Ladder logic. **<u>Week of Thanksgiving</u> Homework project –**
14.	Class seminar, discussion and presentations **Homework project –**
15.	**Case study – <u>Omron CQM PLC Series</u>** - Instruction set, Addressing, delay function, etc.) Application – Motion control of a robot system. **Homework project –**
16.	**Exam #4**

3. Project Plan, Progress and Results

Table 2 highlights a detailed plan for the undergraduate research experience linked to an introductory course on power electronics. During the second week of classes students were given access to a variety of power converters – printers, PC power supplies, PWM drives, etc., from which to choose. Students were also encouraged to consider other converter choices such as mobile telephones that may be appropriate for the modeling research.

About the third week of classes one of the EE graduate students defended his masters' research entitled: "A flyback switch mode power supply model using simulink." It was both coincidental and providential for the class. The presentation was precisely focused on the objectives of the research, as it offered opportunity for asking targeted questions and clearer insights into modeling from a power supply design engineer.

It was quite remarkable that students were able to quickly locate an ample amount of helpful online resources – full schematics of switched power supply, circuit equivalent models for motherboard, test procedures for PC power supply, data sheets for components, complete PSPICE model for converters, etc. All the teams enthusiastically shared insights on various aspects of the modeling. Equipment failure was recorded with several of the power converters selected for the project such as DC motor drives, power supply for printer and PC switched-mode power supply. A substantial amount of time was lost to debugging and repair of faulty converter systems, which in most cases resulted in discarding them for another one. It should be noted that the students were generally reluctant to quickly discard problem converters without first identifying a reason for the malfunction. In many cases it was unclear whether the damage existed before the converters were assigned to students.

Students were very quickly overwhelmed by the number of components in the PC switch mode converter. The converter ended up being far too complex for a few of the students. The equipment damages recorded were mostly from teams with members who were unfamiliar with troubleshooting of circuits. The successful groups had at least one team member that showed some familiarity with troubleshooting of electronic circuits.

Table 3 and Table 4 show snapshots from a report submitted at the conclusion of the course. Students were successful in identifying the interconnections between key components of their power electronic converter, and relating them to the basic converter topologies from their textbook. Some of the teams designed and conducted a series of detailed experiments that demonstrated good grasp of modeling objectives.

Table 2. Project specification – fall 2004.

E ENG 463 **Power Electronics** **Short Projects**

Study and Modeling of typical Power Converters

This project is designed to motivate students to find connections between materials presented in class and typical power electronic subsystems found in consumer appliances and industrial processes. The plan is to complete each section (or mini project) within a week or two, as designated by the instructor. By the conclusion of the semester the student should be able to conduct performance tests on real power electronic systems as well as develop computer simulation models that may be useful for design or redesign.

1. Select a power processing (converter) system such as input power module for cell phone, personal computer, adjustable speed drive, etc.

2. Open up the converter system without destroying it and identify and list major sections or modules of the converter circuit such as input, output, filters, switching devices, control circuit, etc. Write the system specification (if available). Find and print specification sheet for major devices – switching transistors, control chips, etc. <u>Record the following in your logbook</u>:
    a. System specification (voltage, current, power ratings, etc.)
    b. Major sections or modules (including part number for major components)
    c. List of major devices and specification sheets

3. Review various chapters of the course textbook and find the circuit topology that best represent your converter system. Redraw the circuit and include variations specific to your converter system. <u>Record the following in your logbook</u>:
    a. Ideal converter topology (PSPICE or SimPowerSystem)
    b. Modified (or enhanced) converter system (PSPICE or SimPowerSystem)

4. Develop a test plan for studying the load response of your converter system. List equipment needed, enumerate test procedure in detail, and specify results you plan to record. As a minimum, plan to record snapshots of input-output waveforms with the digital storage oscilloscope, record waveform harmonics and other load performance indicators. <u>Record the following in your logbook</u>:
    a. Objective (or goal) of the experiment
    b. List and specification of equipment needed
    c. Test (or experimental) procedure
    d. Applicable circuit diagrams
    e. Data collection
    f. Summary and observations

5. Develop a MATLAB-Simulink model of your converter system. Conduct load studies identical to the laboratory plan previously completed. Generate and document results. Compare simulation with experimental test results (harmonics, power factor, etc.) and discuss your observations. <u>Record the following in your logbook</u>:
    a. Printout of MATLAB Model file (show values of all parameter)
    b. Printout of Scope plots (clearly labeled and organized)
    c. Compare experimental with simulation results. Discuss your observations.

6. Develop a PSPICE model of your converter system. Conduct load studies identical to the laboratory plan previously completed. Generate and document results. Compare simulation with experimental test results (harmonics, power factor, etc.) and discuss your observations.

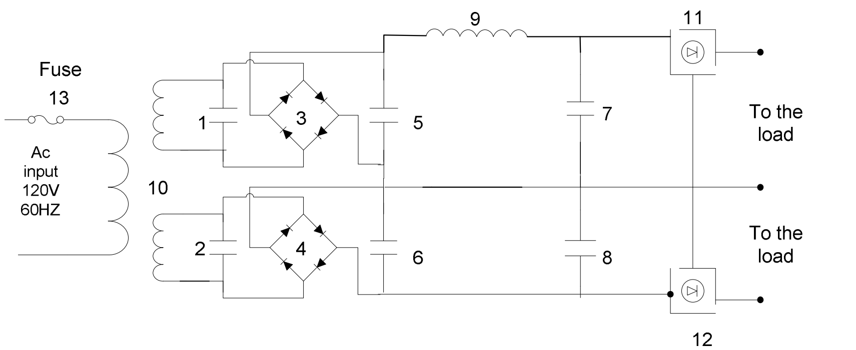
    Repeat Part 5 with PSPICE modeling environment

7. Refine your MATLAB-Simulink model by adding more details from your converter system. Conduct load studies and discuss improvements in simulation studies.

    Document results and discuss improvements

Table 3. System components, specifications and circuit.

Components	Specifications
1, 2	AC capacitors 0.22 uF - 250V 60/50Hz
3, 4	Rectifier Bridges, each with 4 semiconductor diodes 5 Amp
5, 6	Filtering capacitors 80 volt - 5600uF; 16volt-1500uF
7, 8	Filtering capacitors 80 volt - 5600uF; 50volt-8200uF
9	Filtering inductor 400 uH
10	Input Transformer (120V 60Hz), Secondary (42V and 9.3V)
11, 12	Voltage regulators (L7805 and 8721).



Converter circuit diagram general description

4. Conclusion

The undergraduate research (modeling) experience proved very valuable in exposing students to a fairly large-scale engineering system beyond what most of them have encountered in their undergraduate studies. The scope of the work offered a challenge to self-motivated students despite the limited background in critical course materials. Some of the students accomplished many of the course objectives.

The choice and type of power electronic systems for modeling is very attractive – converters from older generation PCs and printers awaiting salvage are available in abundance; the low cost and general inconsequential risk of damage make the category well suited for experimentation by undergraduate students.

There is however much that can be done to improve the research experience for the undergraduates in future sessions of this laboratory course. Since there is a large number of PC power supply available for use, the course syllabus could be revised to ensure early coverage of switched mode power supplies. The experience would have been less trying for some of the students if the power converters were certified problem-free before being considered for the modeling task. More attention will be devoted to pre-testing in the future.

Most of the students considered the exposure very beneficial. The summary of opinions is best captured in the following statements by the students:

"This was a very interesting learning experience and proved to be very useful."

"I think that I have gained a valuable amount of knowledge from this experimentation experience."

5. Acknowledgment

Table 3 and Table 4 are edited portions of project report submitted by Hisham Falah and Joseph Ateia who were students enrolled in the power electronics course in the fall 2004 semester.

6. References

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7. Biography

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Table 4. Sample of Documented Results.

Part 4: The Test Plan

Objective: To observe and simulate the converter performance under full load, and no-load conditions.

The First Test: The no load condition

Both the two motors and the control circuit will be totally disconnected from the circuit. The transformer will provide the supply for the two rectifiers, the output waveforms and the dc voltage level at the output of each rectifier will be observe.

Equipment: 1-Computer printer. 2- Digital Millimeter- Keithly 169. 3- Digital oscilloscope- Tektronix TDS 3012 B (# 1315). 4- Solder station. 5- Tools.

Procedure:

1. **The no load response without the filtering circuit:**
   (Details omitted)
2. **The no load response with the filtering circuit:**
   (Details omitted)
3. **Voltage Regulator effect:**
   (Details omitted)
4. **Data collection:**
   (Details omitted)

The Second Test: The load condition

(Details omitted)

Part 5

In this section of the project simulation for the power supply has been performed. The simulation was done for the converter according to the status of the load and the filtering circuit. SimPowerSystem was used as the main simulation software appropriate. The circuit was simulated as follows:

1- The converter without the filtering circuit under no-load conditions.
2- The converter with the filtering circuit under no-load.
3- The converter under full load with the filtering circuit.
4- The actual load is a step motor with the specification mentioned before, Table1-1. In the simulation environment the load was represented by an inductance and sample value resistance.
5- The harmonic content of the output was observed by simulations, and it is captured a long with the practical results for further analysis.

Summary and Observations

(Parts omitted)

Practically, output1 exhibits harmonic content of the 6^{th} harmonic as 3.85 V, which is bout 5.7% of the practical dc level (62Vp). For the 9.3V converter, the harmonic content by simulation shows the same even harmonic percentages. Practically, the measurement was done for the fundamental harmonic voltage level, the DC content, which is found equal to 11.3 volt. It is fairly the same value as the simulation showed it.

(Parts omitted)

The converter with filtering circuit under no-load conditions:

(Parts omitted)

The harmonic content by simulation reduced to 55.5% for the 2^{nd} harmonic, 38.24% for the 2^{nd}, 16.99% for the 3^{rd}, and 3.72 % for the 4^{th}. The filtering circuit redistributes harmonic content of the signal between the even and the odd harmonics. The practical picture of the harmonic content is shown in the figures- 8, and 9. The result of the filtering is obvious in the clean harmonic waveform. The fundamental is 44.4Volt while the 3^{rd} and the 5^{th} are 2 volt.

(Parts omitted)