



Development of a New Power Electronics Curriculum Relevant to Tomorrow's Power Engineering Challenges

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I. Introduction

This paper presents the results of an effort to develop a new power electronics and electric machines curriculum at two collaborating academic institutions, namely, Purdue University, West Lafayette, Indiana¹, and Iowa State University, Ames, Iowa², hereinafter referred to as Institutions A and B, in a bid to enhance the relevance of this subject to the undergraduate population. This is achieved via identifying the role of power electronics and machines in addressing tomorrow's grand engineering challenge of sustainable energy use. This is a timely and important topic because of the increased demand for highly qualified personnel and the anticipated severe workforce shortage issue in the electric power industry.

Over the past decade, many academic institutions have tried to improve their power electronics curricula, and to include experimental-based learning. (Here, for the sake of brevity, the term "power electronics" also encompasses the technology of machines and drives.) Several institutions, due to budget limitations and/or to mitigate electrocution or mechanical hazards related to higher voltages or rotating machinery, respectively, have developed laboratories with small-scale motors³ or "virtual" laboratory facilities⁴. These are closely related to "e-learning" or Web-based approaches, such as the one developed at the Swiss Federal Institute of Technology (ETH) in Zurich, where a Java-based applet was designed to help students grasp the main aspects of power electronic converter design^{5,6,7}. The same group has developed a series of freely available applets and instructional modules called Interactive Power Electronics Seminar (iPES)⁸. However, the value of simulation-based approaches is reduced if the student does not have a clear physical feeling for the hardware of the system that is being simulated⁹.

Our developed laboratories borrow elements from several other educational approaches, which are discussed here in more detail:

- At the University of Illinois at Urbana-Champaign, power electronics and machines are taught using a so-called "blue-box" approach¹⁰. A blue box "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." In this educational approach, "students focus on system-level design and eventually can replace the blue box with discrete equivalents to understand the salient design issues." The blue-box approach strikes a nice balance between a system-level and a component-level perspective, and allows instruction of system integration and control concepts.
- At Montana State University, an energy conversion course was designed based on Kolb's learning style inventory, so that a balance was achieved between several activities that appeal to all learning styles¹¹. The course was designed around an inquiry-based learning process that follows four basic steps: (i) concrete experience using a real-world example; (ii) abstract conceptualization with "just-in-time" analytical theory; (iii) reflective observation via a team assignment; and (iv) active experimentation in the laboratory.

- At Chalmers University of Technology in Sweden, an experiment has been devised to engage graduate-level (MS) students in designing a power electronic flyback converter¹². The experiment is based on the “Conceive – Design – Implement – Operate” (CDIO) Initiative¹³, which encapsulates a complete design process, similar to a real-world engineering problem-solving scenario. An operational flyback converter is initially provided to the students, who are then asked to improve its performance in several ways. Inspired by this, we have designed similar problems for the undergraduate courses, albeit simpler.
- At Clemson University, an electric machines laboratory was developed that uses industrial-grade equipment and emphasizes power electronics and drives¹⁴. An interesting observation made therein was that even though older electric machines may be perfectly functional, student interest can be negatively impacted by the appearance of the equipment. Therefore, to attract new students to our area, it is important to utilize state-of-the-art and industrial-grade equipment.
- At the University of Minnesota, an integrated Electric Energy Systems curriculum has been developed, which follows a top-down, systems-level approach to highlight interrelationships between power electronics, electric power systems, and electric machines and drives¹⁵. Specifically, the topic of power electronics is intended to cover both the fundamentals and practical design in a single-semester course. The experimental part of the course is based on using a pre-fabricated reconfigurable power electronic board called the “Power-pole board” to implement various power electronic circuits.

Our pedagogical approach seeks to combine industrial-grade technology with collaborative and interactive learning strategies. A problem-solving flavor is added in our teaching approach, as opposed to more traditionally structured lectures. We include research-based sequential assignments and collaborative design projects to encourage student engagement inside and outside of the classrooms, and to promote student self-discovery. This educational approach provided additional hands-on experiences to motivate students and help contextualize the course materials, and opportunities to explore a selected set of topics in greater depth.

Here, we describe our experiences in: (i) establishing an approach to teach/learn fundamentals of power electronics in the context of several applications including renewable energy conversion and transportation electrification; and (ii) tailoring analytical/experimental tools to enhance active design/research-based learning using industrial-grade equipment.

This paper is structured as follows. In Section II, after some general remarks, we proceed by presenting first the curricular development on power electronics, and then the curricular development on machines and drives. We discuss how this material was adapted for teaching two courses with different syllabi at the two collaborating universities, the first focusing on power electronics, the second being a combined power electronics and machine drives course. Course assessments were conducted on a regular basis by an external evaluator, under a thorough evaluation plan that included formative and summative assessments. The assessment outcomes are presented in Section III.

II. Background Information and General Remarks

The power programs in the electrical and computer engineering departments at both institutions were in need of a new educational approach for bringing timely topics such as renewable energy conversion and vehicle electrification concepts into the undergraduate classrooms. In this respect, power electronics as a key enabling technology was identified as a course with high potential to make an impact. The goal of integrating these concepts into the undergraduate power engineering curriculum was achieved by (A) transforming current course syllabi to reflect the role of power electronics as a core enabling technology for renewable energy conversion and electrified transportation, and (B) creating innovative laboratory facilities and exercises for reinforcing the theoretical aspects taught in the classroom lectures.

A. Restructuring the Course Syllabi

Transforming the current course syllabi was achieved by revision of the course content and adding research-based sequential assignments and design projects. For example, at Purdue University, the students first learned about the fundamentals of operation of dc-dc buck and boost converters, photovoltaic modules and Maximum Power Point Tracking (MPPT) techniques during the course lectures. They also became familiar with practical applications of converters and computational tools for the simulation and design of power electronic converters. Then, in a subsequent research-based assignment, the students were tasked to apply their knowledge to a slightly different converter topology, e.g., an interleaved boost converter or a three-level buck converter. These converters were not explicitly taught in the classroom; instead, only basic concepts of operation, analysis, and control techniques were taught. During a subsequent assignment, the students were tasked with designing a converter for a photovoltaic module, and implemented basic MPPT techniques. With these sequential assignments, the students got involved in self-study, performing literature reviews, design considerations, and control techniques of the power electronic circuits at a deeper level, and gained an invaluable experience in analyzing and solving real-world problems slightly outside the context of the lectures but still in a safe learning-based environment.

B. Creating Laboratory Facilities and Exercises

The developed laboratories consist of several identical power electronic stations, such as the one shown in Fig. 1 from Iowa State University. Each station accommodates two or three students, and consists of a computer for control and data capture/analysis, an oscilloscope for observing/capturing the waveforms, sensing equipment including current and voltage measurement probes, multi-meters, loads including dc and ac motors, batteries, a Texas Instruments (TI) C2000 micro-controller board, passive components, semiconductor devices, and Printed Circuit Boards (PCBs).

Power electronic circuits are designed and simulated in the MATLAB/Simulink environment with the SimPowerSystems¹⁶ and ASMG toolboxes¹⁷, which contain models of typical power system elements, such as transformers, electric machines, and power electronic devices. The implementation procedure adopted for digital control of power electronic circuits is based on the automatic code generation capability of MATLAB embedded coder, which allows the Simulink models to be converted directly into C code¹⁸. Subsequently, the C code is automatically com-

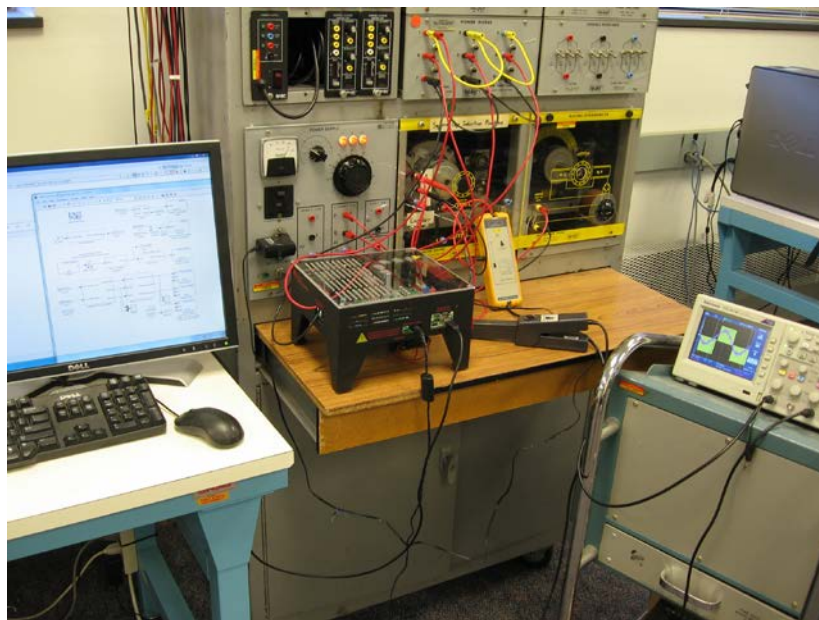


Fig. 1. Photograph of an experimental station at Iowa State University.

piled into executable code for the micro-controller unit (MCU), then assembled, linked and downloaded. The Target Support Package (TSP) in MATLAB/Simulink for the TI C2000 micro-controller allows the students to deploy pre-built MATLAB/Simulink component models for executable code generation. Using the TSP library and its TI C2000 subset, students can communicate with and control their prototyped power electronic circuits in real time by linking to the Code Composer Studio (CCS) program¹⁹. The CCS includes a suite of tools used to develop and debug embedded applications for the TI hardware tools. It includes compilers for each of TI's device families, source code editor, project build environment, debugger, profiler, simulators, and many other features.

The laboratories are weekly 3-hr long sessions. The students are assigned a pre-lab exercise, which usually consists of prerequisite reading material, such as going through user manuals, datasheets, and other time-consuming but necessary activities. They work collaboratively in groups of two or three per experimental station, and are supervised by a teaching assistant. However, each lab requires an *individual* submission of a number of deliverables, clearly identified in the lab manuals. Typically, the deliverables themselves require the successful completion of experiments in software and/or hardware. The questions asked in the deliverables require some thought to complete, and they go a step further than just describing what happens in the experiment, by making the students reflect on the observed behavior of the systems. Finally, each lab concludes with the following question, which the students have 15 minutes to answer: "Write about one or two things you learned in this lab that you think are important or interesting, and why." It should be noted that the lab sequence is not entirely modular. Rather, each lab builds on knowledge acquired from the previous sessions. Therefore, laboratory experiments become increasingly complex, in conjunction with a parallel increase of the students' familiarity with the equipment and expertise on the subject matter. This also helps maintain the students' interest and participation.

TABLE I: TIMING AND SEQUENCE OF LABORATORY MATERIALS IN BOTH INSTITUTIONS.

Week	Institution A (Purdue University): power electronics-only class	Institution B (Iowa State University): single class combining machine drives and power electronics
1	PE1	PE1
2	PE2	PE2
3	PE3	PE3 (emphasis on figures of merit)
4	PE4 – part I	PE4 – part I
5	PE4 – part II	PE4 – part II
6	PE4 – part III	PE4 – part III
7	PE5 – part I	PE6 (three-phase inverter) – part I
8	PE5 – part II	PE6 (three-phase inverter) – part II
9	PE5 – part III	MD1
10	PE6 (single-phase inverter) – part I	MD2
11	PE6 (single-phase inverter) – part II	MD3
12	PE6 (three-phase inverter) – part III	MD4
13	PE6 (three-phase inverter) – part IV	MD5 – part I
14	Final project – part I	MD5 – part II
15	Final project – part II	MD6

The laboratory sessions consist of a sequence of design problems. The manner in which these exercises were conducted in our two institutions is provided in Table I. At Institution A, the course was dedicated to power electronic converters, whereas at Institution B, it included machine drives as well. The labs were developed with the help of graduate research assistants.

The lab experiments encapsulate complete systematic design and implementation processes. In general, one can identify two sets of labs, one for power electronics (PE), and one for motor drives (MD), briefly described below.

Lab PE1: Introduction to Power Electronics Simulation Software. The objective of this lab is to introduce basic concepts of computer simulation of power electronic circuits using MATLAB/Simulink and an add-on specialized toolbox called the Automated State Model Generator (ASMG). First, a simple model from the Simulink Getting Started Guide is built, and students are asked to identify the significance of simulation parameters, such as the simulation step size, based on their observations. Then, two simple power electronic circuits are simulated.

Lab PE2: Introduction to the TI F28035 MCU. This lab provides an introduction to embedded code generation using the TI F28035 Experimenter Kit, Code Composer Studio (CCS), and MATLAB/Simulink Embedded Coder, by executing a simple program to blink an LED. The TI F28035 Experimenter Kit is used as the main digital controller to control the power electronic devices in the lab. The CCS Integrated Development Environment (IDE) is used to generate an executable file and program the MCU. The learning objectives of this lab are: (i) To learn general features and capabilities of microcontrollers, especially the F28035 MCU. (ii) To generate, build, and debug an embedded application using MATLAB and CCS. (iii) To use Embedded

Coder to quickly develop an embedded application, and generate executable code for the F28035 MCU.

Lab PE3: Figures of Merit and Introduction to Gate Drivers. This lab is meant to serve as a gentle introduction to safely and efficiently working with hardware in the lab, so relatively simple experiments are conducted. Experimental waveforms are observed and transferred from the oscilloscope to the PC, where their figures of merit are evaluated using MATLAB code written by the students. This lab also provides an introduction to gate drivers, differences between low- and high-side gate drivers, and their applications. The learning objectives of this lab are: (i) To use a digital oscilloscope to measure voltages and currents, and extract waveforms. (ii) To calculate various figures of merit of dc and ac waveforms (e.g., rms value, ripple factor, and total harmonic distortion) using MATLAB scripts. (iii) To use low- and high-side gate drivers to control MOSFETs.

Lab PE4: Buck Converter. This lab is a sequence of three lab sessions that involve the complete design, simulation, and implementation of a dc-dc buck converter. In Part I (the design stage), and as a pre-lab assignment, students design the buck converter with a set of given requirements. Based on the design requirements and using the fundamental calculations taught in class, the converter components are sized and determined. Subsequently, the designed circuit is simulated in the MATLAB/Simulink environment. Based on the component's datasheets, the MOSFET on-state resistance and diode forward-biased voltage drop are included in the simulation. The effect of component nonidealities on the operation and efficiency of the converter is observed and analyzed. In Part II (the software implementation stage), a controller is developed for the buck converter that was designed in the previous lab session. All controls are developed using the MATLAB/Simulink Embedded Coder toolbox. The TI High-Voltage Motor Control and Power Factor Correction development kit (TMDSHVMTRPFCKIT), which includes the F28035 ControlCARD, is used to implement the design in Part III. The programmed controller is connected to a buck converter built using Lab-Volt passive components. The converter feeds a dc motor, so the students can observe the impact of a varying output voltage on the motor's performance. This also serves as a first contact with motors, without requiring any knowledge whatsoever of dc machine theory. The learning objectives of this lab are: (i) To understand the basics of PWM waveforms. (ii) To design and simulate a dc-dc buck converter and ensure that the requirements are met. (iii) To design an embedded controller using MATLAB/Simulink Embedded Coder. (iv) To configure the enhanced Pulse Width Modulation (ePWM) and Analog-to-Digital Converter (ADC) peripherals on the Piccolo F28035 ControlCARD. (v) To construct the dc-dc converter and run experiments. (vi) To study the converter's performance by comparing the experimental results with the simulation results and analyze their differences.

Lab PE5: Boost Converter. Using a similar procedure to Lab PE4, this lab consists of a sequence of three lab sessions devoted to a complete design, simulation, and implementation of a dc-dc boost converter.

Lab PE6: Single-Phase and Three-Phase PWM Inverters. This lab consists of a sequence of four lab sessions and involves simulation and implementation of single-phase and three-phase PWM inverters. For the single-phase inverters, the students are tasked to simulate the bipolar and unipolar PWM strategies for an H-bridge inverter and observe/analyze the inverter performance. For the three-phase inverters, a simulation of a three-phase inverter that uses a space vector

modulation (SVM) strategy is developed. The MATLAB/Simulink model of an implementation of a SVM inverter (whose principles, such as qd -axes theory, should have been already taught in class) is provided to the students, and they are asked to dissect its code components. For hardware implementation, unipolar/bipolar PWM single-phase and three-phase inverters are implemented. This is done using the TI F28035 ControlCARD. The embedded application is developed using MATLAB/Simulink Embedded Coder. The single-phase and three-phase inverters are connected to an RL load and a squirrel-cage induction machine, which is driven using a simple V/f control strategy. The learning objectives of this lab are: (i) To learn the intricacies of simulating a PWM inverter. (ii) To use blocks with discrete sampling in Simulink (i.e., understand concepts of continuous-time vs. discrete-time components). (iii) To use the TI F28035 to implement a PWM strategy for an inverter. (iv) To introduce the squirrel-cage induction machine.

Lab MD1: Squirrel-cage Induction Machine – Steady-state Performance. In this lab, students analyze the steady-state performance of the squirrel-cage induction machine (SCIM), which is the most widely used type of motor in the industry. The learning objectives of this lab are: (i) To become familiar with the squirrel-cage induction machine equivalent circuit. (ii) To use the TI MCU to drive the machine at different conditions. (iii) To measure the torque-speed curve and other steady-state quantities (e.g., power factor, input current).

Lab MD2: Quadrature Encoder Basics. Machine control techniques often require accurate speed and/or position feedback information. In this lab, students learn how to use a quadrature encoder to determine rotor speed and angular position. These concepts and methods can be applied to any machine equipped with a quadrature encoder. The learning objectives of this lab are: (i) To use a quadrature encoder to measure rotational speed and angular position. (ii) To use the TI C2000 enhanced Quadrature Encoder Peripheral (eQEP) to process encoder data.

Lab MD3: Squirrel-cage Induction Machine – Dynamic Performance. In this lab, students simulate the dynamic response of the SCIM using MATLAB/Simulink and ASMG. The learning objectives of this lab are: (i) To introduce dynamic models of induction motors (in contrast to the steady-state equivalent circuit). (ii) To study the response of an induction motor during start-up and changes in mechanical load.

Lab MD4: Induction Machine Parameter Identification. The SCIM equivalent circuit parameters are obtained through a series of measurements. These parameters can be used to simulate motor performance, and aid in the design of motor drive applications. The procedure described here is based on IEEE Standard 112-2004²⁰ (a pre-lab assignment asks the student to study certain sections of this document). The learning objectives of this lab are: (i) To perform a locked-rotor test, no-load test, and load point test. (ii) To analyze the measurements to obtain the squirrel-cage induction machine parameters for use in the equivalent circuit.

Lab MD5: Squirrel-cage Induction Motor – Field-oriented control. In this lab, a closed-loop speed controller using Field-Oriented Control (FOC) is implemented. The TI High Voltage Motor Control and Power Factor Correction kit (TMDSHVMTRPFCKIT) comes with a set of CCS example projects, including a FOC application pre-tuned for the Marathon Electric 5K33GN2A SCIM. This project is incrementally built using CCS, and runs on the F28035 MCU. The machine's response to a load step change is analyzed. Due to the complexity of this exercise, it is

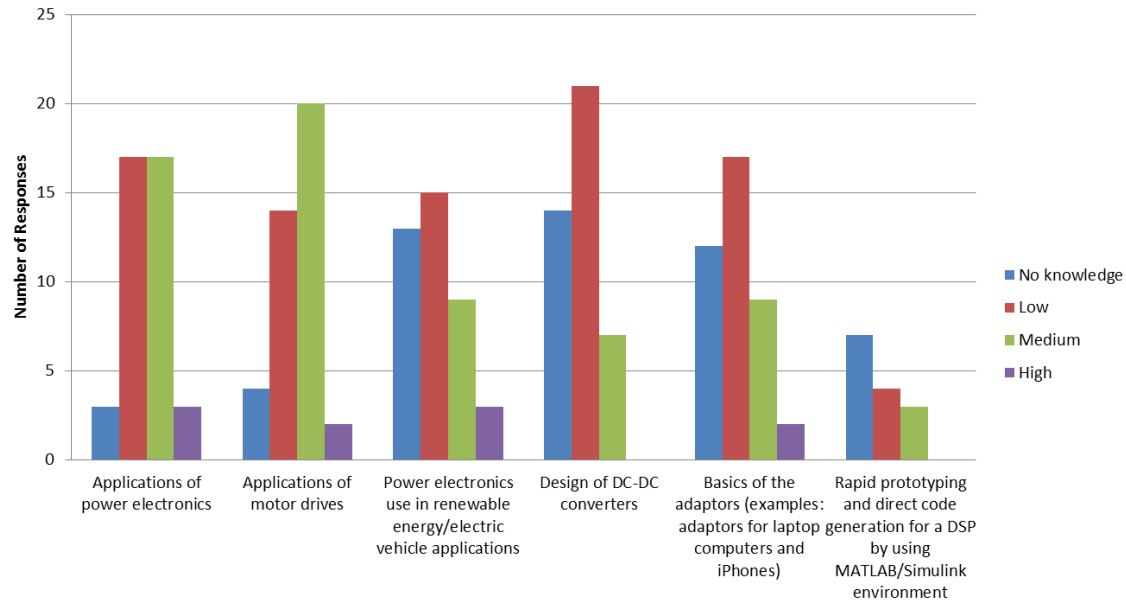
completed in two sessions. The learning objectives of this lab are: (i) To learn about FOC through a CCS example project. (ii) To use CCS to incrementally build the project, and view system variables in real time. (iii) To analyze the dynamic response of the machine for a varying load.

Lab MD6: Design of a Motor Drive for an Electric Vehicle. This lab asks students to combine all of their in-class and laboratory work, and is open-ended. They develop a theoretical EV motor drive. This design draws upon their acquired knowledge of power electronics, pulse width modulation techniques, system modeling and analysis, MCU-based control, and performance measurements and analysis. The learning objectives of this lab are: (i) To develop a detailed plan/procedure for development of an EV drive system. (ii) To combine knowledge gained in this class, with methods and techniques learned in other classes.

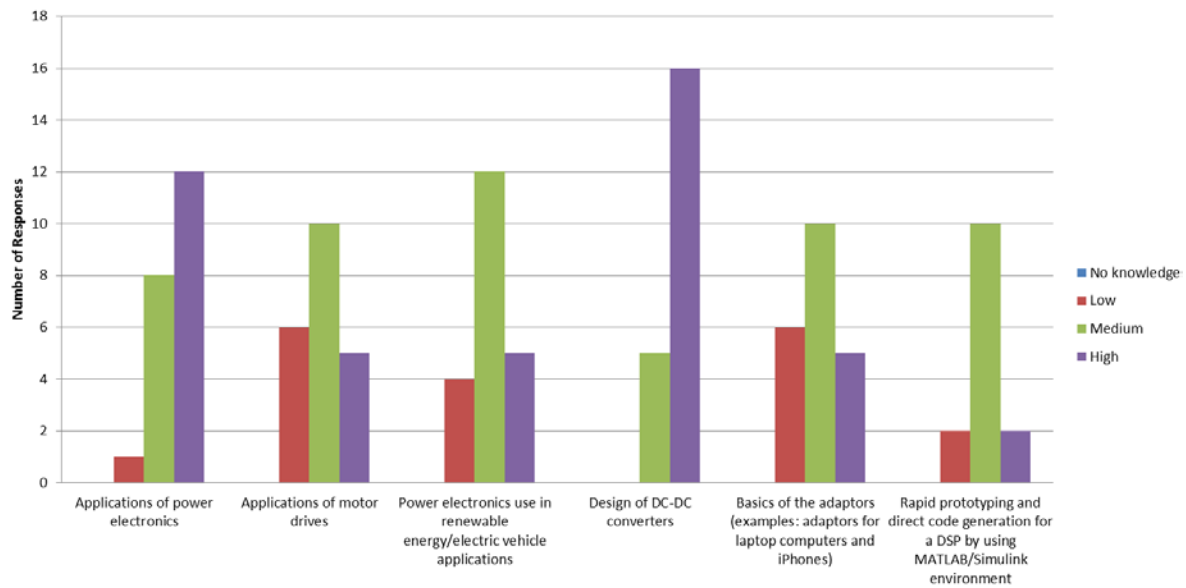
Final project: Design of a Converter to Drive LED Lighting Systems. This design project consists of a sequence of two lab sessions that involves complete design, simulation, and implementation of a dc-dc Single-Ended Primary-Inductor Converter (SEPIC). At the design stage and as a pre-lab assignment, the students are tasked to design a SEPIC with a set of given requirements. The design requirements are based on the specifications of the LEDs that need to be driven. Based on the design requirements and using the fundamental calculations taught in class, the converter components are sized and determined. Subsequently, the designed circuit is simulated in the MATLAB/Simulink environment. At the software implementation stage, controllers for the SEPIC and PWM dimming of the LEDs are developed using the MATLAB/Simulink Embedded Coder toolbox. The TI LED Lighting Developer's Kit with the F28035 ControlCARD is used to implement the design. The learning objectives of this design project are: (i) To design and simulate a dc-dc SEPIC using MATLAB/Simulink. (ii) To get familiar with LED dimming techniques and configure the PWM dimming on the F28035 ControlCARD. (iii) To construct the converter and run the experiments. (iv) To analyze the impact of PWM dimming on the luminous efficacy of the LEDs.

III. Course Assessment

To ensure that the pedagogical objectives of the course and the laboratory were fulfilled, the students' learning experience and the instructional approach were closely monitored during the Spring 2012 semester, based on a pre-assessment and post-assessment inventory. The pre-assessment inventory, i.e., knowledge/understanding of power electronic applications and concepts in Institution A, and knowledge/understanding of electrical machines and power electronic applications in Institution B, was used as the baseline data. The concepts highlighted in each inventory were applications of power electronics and motor drives, power electronics use in renewable energy/electric vehicle applications, design of dc-dc converters, basics of adaptors (e.g., adaptors for laptop computers and iPhones), and rapid prototyping and direct code generation for an MCU by using the MATLAB/Simulink environment. The results of the assessment are shown in the charts of Figs. 2 and 3 for Institutions A and B, respectively.

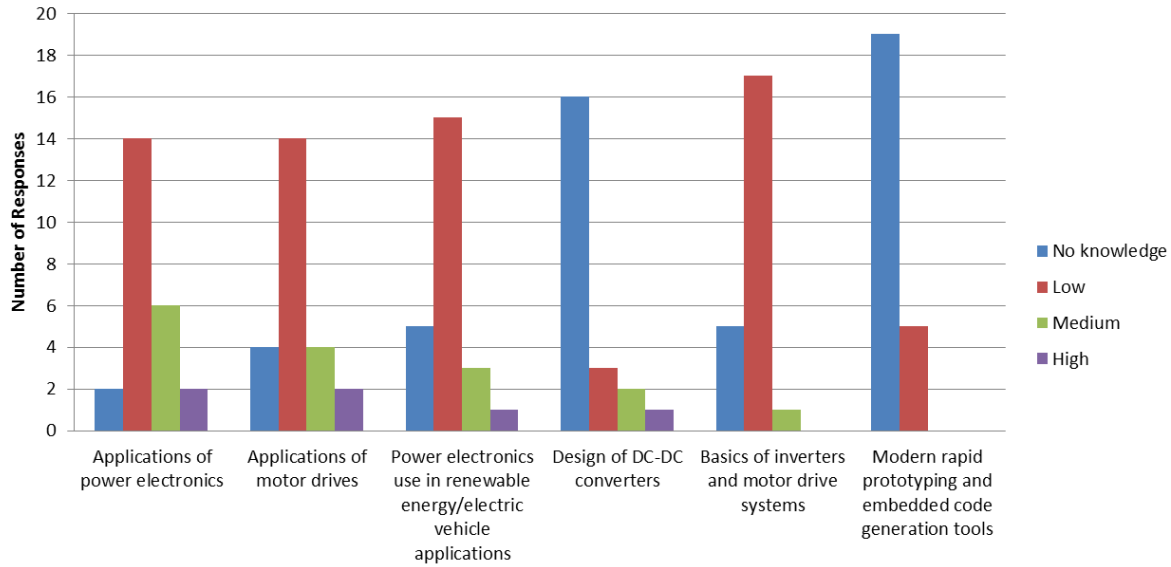


(a)

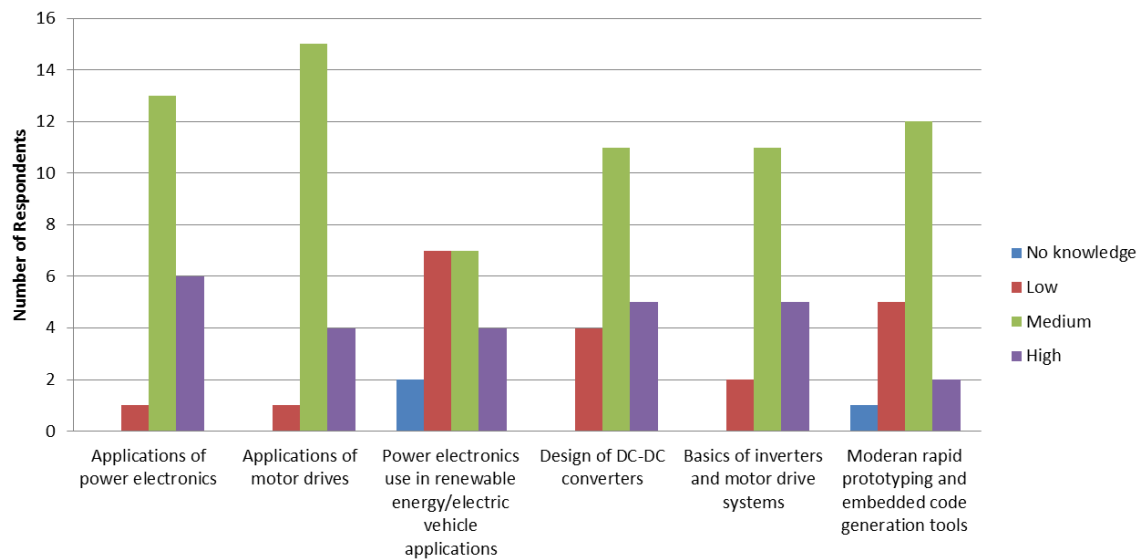


(b)

Fig. 2: (a) Pre- and (b) post-assessment inventory of knowledge/understanding of applications of power electronic concepts in institution A.



(a)



(b)

Fig. 3: (a) Pre- and (b) post-assessment inventory of knowledge/understanding of electrical machines and power electronic applications in institution B.

Through the survey and a small group analysis discussion of the new laboratory in both institutions, the following themes emerged: ‘fast and easy to use’ and ‘very practical’, ‘well-designed for learning and demonstration topics’, ‘learning how to use the device’, and ‘learning about new programs and plug-ins for MATLAB to program and control the board’.

Institution-wide course and instructor evaluations were also used to identify the weaknesses and strengths of the laboratory, and to enhance the learning/teaching environment for future years.

IV. Conclusion

In this paper, the key components of a new power electronics and electric machines curriculum at two collaborating academic institutions were described. The curriculum development is based on restructuring the power electronics course in the context of several applications including renewable energy conversion and transportation electrification. A new laboratory was established to enhance active design/research-based learning using industrial-grade equipment. Course assessments and student evaluations were conducted in both institutions by an external evaluator and under a thorough evaluation plan that included formative and summative assessments.

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