# AC 2009-792: A PROJECT-BASED POWER ELECTRONICS COURSE WITH AN INCREASED CONTENT OF RENEWABLE-ENERGY APPLICATIONS

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# A Project-based Power Electronics Course with an Increased Content of Renewable Energy Applications


## Abstract

This paper will described a project- and problem-based learning approach in teaching power electronics for upper-level undergraduate students enrolled in the applied engineering technology program at our university. This course will have an increased content of applications of power electronics in renewable energy conversion systems. Power electronics, still an emerging technology is multidisciplinary in its nature and the design and analysis of power electronics circuits include the applications of circuit theory, electronics, control theory, electromagnetics, semiconductor devices, microprocessors, numerical methods, signal processing, computer simulation, heat transfer, electromagnetic compatibility, and artificial intelligence. However it is also important to teach students the different fields in which technology is used, e.g. adjustable speed drives, switched mode power supplies, or power electronics for renewable energy. Experience has also shown that students have a difficult time with power electronics mostly because of the maturity the subject demands. A natural and efficient way of teaching power electronics is the problem-oriented and project-based learning approach. Students are often unaccustomed to assimilating materials from many areas at one time, thereby making it difficult for them to simultaneously bring together the circuit, signal and system analysis, electromagnetics and control theory topics which are required to fully describe the operation of a power electronic converter. The project-based course and laboratory described in this paper directly addresses these difficulties by helping students to reduce theory to practice. This approach supports the prerequisite lecture material and allows study of some practical issues which are best handled in a laboratory setting. The course format makes the students gradually more responsible for the analysis and design of control circuitry which permits nominal operation of generic power converters. The laboratory experience will culminate in projects where students analyze, design, simulate and demonstrate power electronics related topics. Each project will be carried out by a team of three or four students. The projects and part of the laboratory experiments will be focused on power applications in the fast growing emerging fields of the renewable industry, such as wind and solar energy or fuel cells. We believe that this will be an efficient approach in teaching power electronics because it can give the students some of the necessary skills the industry is asking for.


## 1. Introduction

Power electronics is the enabling technology for the efficient generation, transmission, distribution and management of electrical energy [1, 2, 4, 7, and 12]. Power electronics has a history that is much older than many of us practicing and teaching in the field today are likely to realize. Its growth and development have not been what one would call smooth and orderly. The ‘life changing” episodes which have brought about the most dramatic changes in the field of power electronics have been largely unanticipated [2, 11]. Today unprecedented technological evolution in power electronics is due to several factors, the recent advances in power semiconductor devices, power system monitoring and control, increased requirements for power quality, new emerging areas of distributed generation and renewable energy requiring new and more advanced and sophisticated power electronics circuits and control systems, and an increasing demand for smaller size and lighter weight for power electronics supplies, coupled with an expanding market demand for power electronics systems. Today more than 75% of all generated power was processed by power electronics. Recent increases in market competitiveness and a growing sensitivity to energy conservation are placing additional complex and stringent requirements on power electronics systems. Moreover, the fast expansion of power electronics into commercial, industrial and residential applications, the pressing needs to develop power systems with low harmonic distortion, as well the increased demand for advanced power electronics converters and controllers for solar, wind and other energy conversion systems has further intensified the interest in this field [4-9]. These extensive uses of power electronics circuits in electronic products, equipment and power systems makes the fundamental understanding of power electronics a necessity for students of all engineering areas, and in particular for electrical and electronics engineers. Presently in great demand are power electronics engineers equipped with knowledge of new and emerging technologies, who understand the environmental impacts, the pressing needs for energy conservation and have general knowledge of the emerging renewable energy technologies and distributed generation. This trend has resulted in an increased interest in attending power electronics courses at the undergraduate and graduates levels, as well as in offering short courses and training for engineers and technicians already on the job.

In response to these demands, universities offering baccalaureate and graduate degrees in electrical engineering must develop curricula to educate a workforce that is well equipped to meet these challenges. Unfortunately, US universities have not kept pace with the growing power electronics field and are not educating students in sufficient numbers to take advantage of recent technologies and power electronics applications, as needed by our industries [2-4, 12]. Rather this growth has been principally research and industry oriented. Little progress is being reported, with very few notable exceptions on the role of educational institutions in either keeping pace with this growth or addressing the importance of introducing new emerging power electronics technologies, applications, and effective classroom and laboratory instruction. Teaching power electronics is somewhat challenging since the field is quite broad and requires significant knowledge in multiple areas of electrical and computer engineering. The job of a course provider is often made more difficult because the theoretical analysis of topics, such as analog electronics, magnetic characteristics, and compensator design, are particularly hard to comprehend without experimental observations. Thus, an effective power electronics course should ideally contain hands-on design and experimental work in addition to the study of theory and simulations [2-9]. The power electronics laboratory course described here attempts to directly address these difficulties by helping students reduce the science to practice. From this perspective, this approach of restructuring the course support laboratory and the inclusion of renewable energy power electronics projects are of critical importance in solidifying the fundamentals of power electronics in the curriculum.

This paper is primarily motivated by the current efforts at our department to restructure and upgrade the current undergraduate course and laboratory and to develop a new graduate-level course in power electronics. It is hoped that this presentation gives the education issue in power electronics the exposure and attention it deserve. The paper describes laboratory experiments in detail, provides short descriptions of the projects and includes some lessons learned, student feedback, and plans for future changes. The author strongly believes that such discussion and feedback from other educators will advance power electronics education through introduction of new topics, laboratory experiments or new power electronics applications, as well the development of new courses and help faculty, especially the younger ones interested in research and teaching in this field.

## 2. Energy Conversion, Power Systems and Renewable Energy Courses

The Power Electronics course, required in our department is part of a sequence of four power systems and energy conversion courses: 1) Energy Conversion; 2) Power Systems Fundamentals, and the new course developed by the author: 3) Introduction to Renewable Energy. All these are core courses and are usually taken by the students in their third or fourth years of study. The objective of the power electronics course is to present and cover the basics of industrial and power electronics over a spectrum of applications and to provide an introduction to the emerging technologies in these fields. The course is accompanied by laboratory work using hardware and/or software simulation tools. Upon completion of this course the students are expected to be familiar with: power computation, power electronics switching devices, DC/DC converters and switch-mode power supplies, DC/AC and AC/DC converters, AC and DC drive systems, and with some of the utility and power applications of power electronics circuits. The energy consumption is steadily increasing and consequently there is a demand to increase the power generation capacity. A significant percentage of the required capacity can be and will be based on renewable energy sources. One other advantage offered by renewable energy sources is their potential to provide sustainable energy in areas not served by the conventional power grid. The growing market for renewable energy technologies has resulted in a rapid growth of power electronics. Wind turbine technology, as the most cost effective of the renewable energy conversion systems, will play an important part in our future energy supply. But other sources like solar, micro-turbines, tidal power, and fuel cell systems may also be serious contributors to the power supply. Power electronics is the key-technology to change the basic characteristics of the wind turbine from being an energy source to be an active power source. Such possibilities are also used to interface, control and condition other renewable energy sources. Notice also that most of the renewable energy conversion systems produce DC power, and hence the power electronics and control equipment are required to convert the DC into AC power. Advances in power electronics are likely to have a significant part in increasing integration of power systems especially within direct current systems and direct and alternating current connections. To address these facts our department decided to offer, as an elective a course in renewable energy. This is part of a new planned program in power systems and renewable energy. Our upper-level undergraduate course on renewable energy and power systems is planned to be offered for the first time in the Spring 2009 quarter. The course primarily focuses on wind energy, wind power systems and solar/photovoltaic energy generation.

Therefore the key areas that the course focuses on are the wind and solar energy sources and their related technologies. The teaching modules of this course consist of the following topics each of them presenting a special type of renewable energy and dispersed generations. The outline of the course includes (ten 3-hour lectures): 1) Basic principles of energy generation; Introduction to renewable energy systems; 2) Electric machines Basics; Electric machines for renewable; 3) Solar energy fundamentals, Photovoltaic energy production; Photovoltaic systems; 4) Wind energy resource characteristics, Wind energy conversion systems: aerodynamic and electric aspects, Wind energy modeling aspects; 5) Fuel cell systems; 6) Distributed generation and power quality. The laboratory exercise will include: 1) Solar cells and panels – MATLAB simulation of solar cells and panels electrical characteristics; 2) Grid-connected PV systems – MATALB simulation; 3) MPPT controller – experimental test; 4) Single-phase grid converter used for PV residential applications; 5) Control of three-phase grid converter used for Wind Energy Conversion Systems; 6) Standalone small wind turbine generator for remote applications – MATLAB simulation. The experimental part of the renewable energy course content and especially the supporting laboratory are relying heavily on the power electronics laboratory. The diagram of Figures 1 shows the topology and structure, as well the main components of a renewable energy conversion system. The power electronics circuitry is heavily present in the system, so the inclusion of such applications in the projects of a Power Electronics course it is not only necessary, but also very useful.

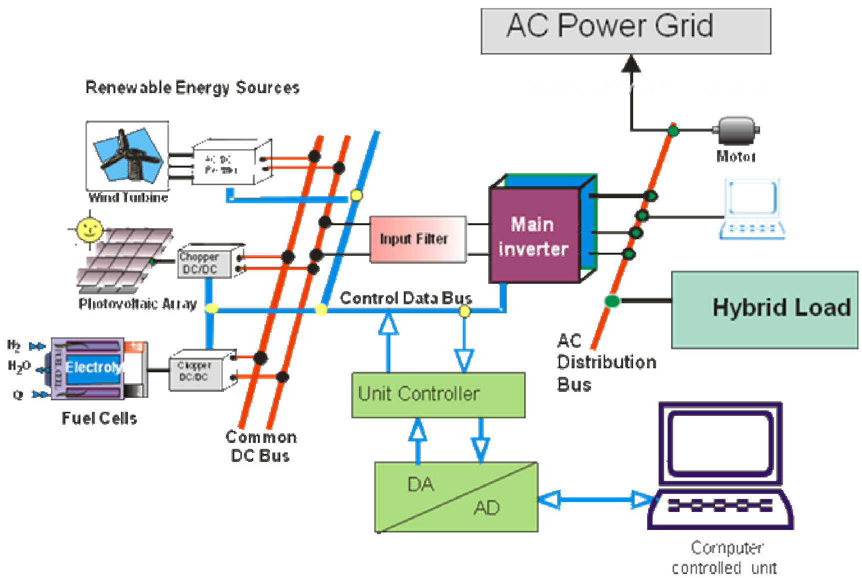


Figure 1: Topology of a Grid-connected Hybrid Renewable Energy Conversion System showing the Power Electronics Circuits

## 3. Laboratory Structure and Project-based Approach of Power Electronics Course

The power electronics laboratory, in our view must be a time-tested mechanism for helping students to assimilate difficult concepts. Laboratory work encourages the students to review previously covered materials from the perspective of trying to understand what they have observed and measured. In addition, working with hardware and instrumentation helps students to deeper understand the physics behind the engineering problems and to acquire skills required in industry. Further, a working knowledge of visualization and simulation tools used during the laboratory provides support for creative circuit analysis, evaluation and synthesis. A simulator is a powerful way to test new ideas without difficulties associated with circuit implementation and building. The laboratory complements and supplements the lecture course, which currently follows the text by Mohan [4]. This text does a particularly good job of examining the principles of power electronics from an integrated and top-down viewpoint. The many examples and problems provided in the book are an excellent support for laboratory experiments and projects.

### 3.1 The Laboratory Goals

The targeted audience for the laboratory is usually a class of twelve to sixteen students divided in teams of two for the laboratory itself and in teams of three or four for the end of term projects. The experiments and projects are detailed in the next section of the paper. The overhaul effort focused on achieving two primary objectives: 1) Updating the course content and re-designing experiments and projects so that students can experience the topics of renewable energy conversion, and 2) Providing ample opportunities for students to learn by doing, i.e. enabling active learning. There were also some secondary objectives of this effort: 1) Updating equipment and experiments, 2) Providing enough equipment for six laboratory groups to simultaneously conduct the same laboratory, and 3) Improving technical report writing skills as well the students' presentation skills. These experiments and projects, as detailed in the next section support the following specific goals of our approach in teaching undergraduate power electronics course:

1. To provide the students with an opportunity to gain design experience through the completion of the project. The project has five components to it: an analytic design, a computer simulation of circuit operation using LabVIEW package, experimental implementation of the circuit, a written report which summarizes the work, and an oral presentation in the last week of the term. The students gradually build the project experience through experiments with an increasing amount of design responsibility.
2. To reinforce and support the lecture based-course in power electronics, via exposing the students to similar materials in a practical setting, rather than exposing them to altogether new materials.
3. To introduce the students to state of the art simulation tools which are employed extensively by the industry. Accurate simulation of power electronics circuits is an extremely important element of the development cycle, due to the time cost and safety issues associated with a new design.
4. To emphasize the importance of corroborating and comparing simulation results with laboratory measurements. Students must gain a simultaneous appreciation for the power and limitations of the simulation software packages.
5. To expose students to the safety and measurement techniques which are important in electrical engineering and in particular in power electronics work.
6. To introduce students through projects in the new growing and exciting fields of renewable energy conversion systems.

The following section discusses how these goals are met through our project-based approach with an increased content in renewable energy applications.

**3.2 Examples of Laboratory Experiments**

Due to the switching nature of the power electronics circuits, the theoretical analysis of this type of converters is difficult to comprehend without experimental observations. Therefore, an effective power electronics course should ideally contain hands-on design and experimental work in addition to the study of the theory and simulations. Fig. 2 shows the block diagram of a typical power electronics system. From Fig. 2, the main components of a power electronics converter are the power stage, the compensation network and the pulse width modulator. The proposed project-based power electronics intends to let the students obtain better understanding of power converter circuits, and will be described in the following subsections.

In the power electronics laboratory we are employing two functional modules for DC-DC converters' and inverters' experiments designed by the MNPRE center of the University of Minnesota (see Figure 3), and a rectifier module, developed at our electronics workshop. Beside these functional modules, reconfigurable test-beds are used by the students to construct, test and design their own converters or power electronics circuits used during the project phase of the course. The cost of these functional modules is rather modest and the equipment and instrumentation employed is the usual one.

The power stage of a typical power electronics converter consists of only passive components (such as inductor(s), capacitor(s)) and power devices (such as switch (es) and diode(s)), as one can see in Figure 2. The use of such prefabricated test-beds and functional modules allows a novice or inexperienced student to assemble a power converter quickly, with minimum risk. The drawback is that such modules tend to become a black box, with mysterious inner workings. To overcome this drawback, new approaches are taken. First, each circuit is examined in details, at least at functional level, before it is used. Second, during the end-of-term design project, as the students gain more experience, each unit of power circuit is implemented with discrete components. As the course and project progress the students design, test and build more and more elements of their power circuit with discrete elements. Based on the concept of reconfigurable and functional module any kind of basic power electronics converters and inverters can be configured through appropriate wiring of the terminals.

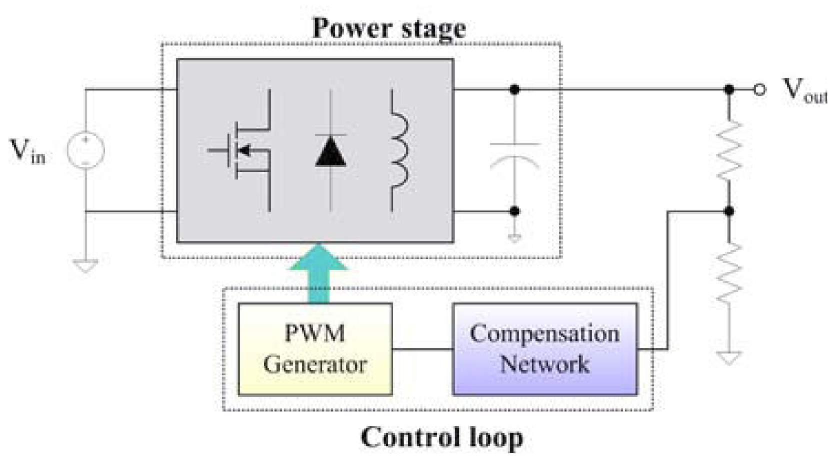


Figure 2 Block Diagram of Typical Converter.

The undergraduate laboratory course has a sequence of four major experiment groupings, each of which is conducted over the course of one week, selected to be complementary with our intention to emphasize the application of power electronics in the renewable energy areas. They are:

a. **Rectifiers:** The first grouping covers diode and SCR rectifier circuits and their renewable energy applications. The operation of diode and SCR are examined and tested. The SCR function module is used to construct and test single-phase and three-phase controlled rectifiers. A battery charger is one of the applications tested with the controlled rectifier.

b. **DC-DC Converters:** Simple buck, boost, buck-boost, or forward circuits are tested through the use of MOSFET function module. The emphasis is on square-wave PWM converters. Switching frequency and design choices of inductor and capacitor values are examined. The experiments lead naturally to the wind and solar/photovoltaic applications. The following module is used for DC-DC converters experiments. This module was developed by the University of Minnesota – MNPRE Center (Figure 3).

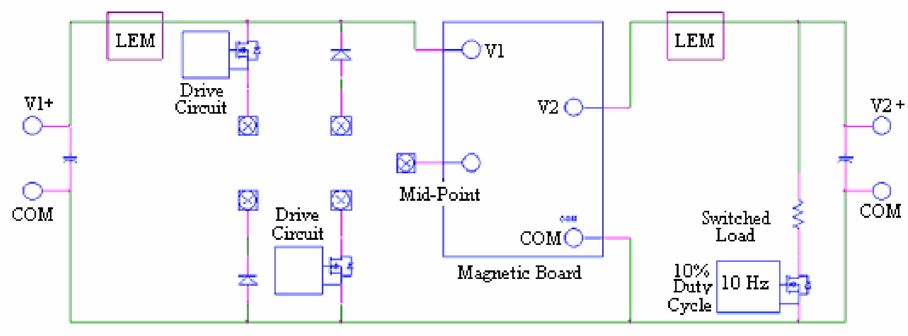


Figure 3: Block Diagram of MNPRE Power-Pole Board

c. **Inverters:** Voltage-sourced square inverters are constructed along with sinusoidal PWM half-bridge converters during the inverter part of the laboratory sequence (see Figure 4). A basic series resonant load is studied. An AC link application is examined as an introduction to isolate DC-DC forward converters. The PWM half-bridge circuit is used to operate a small AC motor and the motor's behavior under frequency variation is studied. Two MOSFET function modules are used in master-slave configuration to enforce complementary switching. A function generator is used to modulate the duty ratio control input of master MOSFET.

The laboratory platforms of the Power Electronics laboratory are set in the Energy Conversion/Electric Machine Laboratory. This not only due to the natural connection between the energy conversion, electric machines and power electronics, but also it is in the intention of the author to develop in near future a fully integrated electric machines, power electronics and renewable energy laboratory.

There are six main objectives in designing the experiments:

1. Emphasize the selection and performances of power semiconductor devices in various load and control conditions.
2. Present a common laboratory hardware station that can be used to study, devices, circuits and controls, and machines and various loads.

3. Provide hands-on experience for students in practical electrical engineering/power electronics applications.
4. Reinforce and support the power electronics course.
5. Expose students to the measurement techniques, data acquisition and safety concerns in power electronics
6. Introduce students to state-of-art simulation tools and software packages as extensively employed in the modern industry.

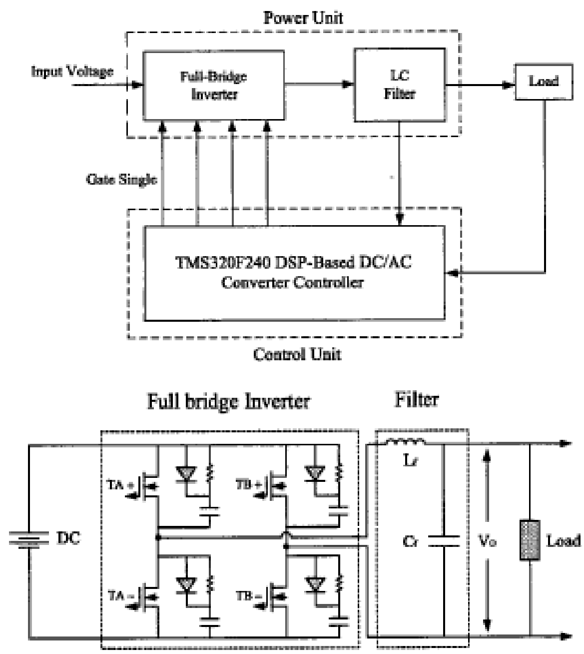


Figure 4: Single Module Inverter System Bloc Diagram (upper panel); Full Bridge Inverter System (lower panel),

The intention of the experiments is to demonstrate to the students the relationship of device characteristics and the device stresses to circuit operation and performances, as well as control techniques used in power electronics. The experiment content offers a blend of fundamental device physics, circuit theory, and measurement techniques with material on established converter topologies and emerging switching techniques. The implementation of these experiments represents collaboration between the faculty and technical staff in our department with feedback from other institutions.

### 3.3 Course Design Projects

To enhance the hands-on experience this course was restructured as a project based course. Students are required to analyze, design, simulate or built a completely functional system, as an end-of-term project, selected from a list proposed by the instructor. The goal of the design project is to explore and enhance students understanding of the fundamental power conversion principles, power circuit simulation capability and hands-on demonstration of circuit prototyping. The course project is worth 15% of the course grade. Students are required to present their project output in a poster session arranged for a technical audience. They are also required to summarize the results of the design in a short report by the end of the course.

During the final month of the laboratory/project-based course, each student team (three to four individuals) is given partial specifications for a renewable energy conversion power electronics application. The team builds it initially with the function module and/or using circuit simulation packages. Each team demonstrates the finished project to the entire class. A short written report summarizing the project is also required as part of the design project. This process synthesizes all of the basic material in the power electronics course and can also be used as part of the requirements of the senior project requirements for each student. Examples of end of term design projects included in this course are:

1. Analysis and Design of Single-Phase PV Inverters
2. Power Conditioning Units for PV Water Pumping
3. PV Maximum-Power-Point-Tracking Controller
4. Line-Commuted Inverter
5. Design a Soft-Starter for an WT Induction Generator
6. Control and Power Electronics of a Small Wind Power for Battery Charging
7. Parallel Inverter System for Large Load
8. Fuel Cell Based Domestic Power Supply

### 3.4 Student Assessment

Table 1 Questionnaire for the evaluation of the Project-based Power Electronics course

| | |
|---|---|
| Q1 | Are the course challenging and interesting? |
| Q2 | Have you learn more than expected with the course? |
| Q3 | Is the team project useful to you? |
| Q4 | Are the lectures of high quality and easy to understand? |
| Q5 | What was the level of “hands-on” feeling experienced the laboratory exercises? |
| Q6 | Please, provide an overall evaluation of the course |

The Power Electronics course, using the new teaching and learning approach was first time offered in the Fall 2008 quarter at the main campus of our university and is offered for the second time during the Winter 2009 quarter, which ends in mid March 2009 at one of the partner college. At the end of the Fall 2008 quarter, all students have been requested to answer (with a five point scale: 1-very poor, 2-poor, 3-satisactory, 4-good and 5-very good) an anonymous questionnaire as shown in Table 1. According to the results, the new project-based approach received a 3.9/5.0 rating, comparing with an average rating of 3.4/5.0 for the all courses at our program. The results from the students' feedback have been extremely positive with the regard to the renewable energy-related projects and the experiments provided during the laboratory sessions. The majority of students felt that such projects enhanced their understanding of the theoretical materials and made the course more interesting. A similar survey will be conducted at the end of the Winter 2009 quarter.

## 4. Conclusions and Future Work

Students learn, verify, and reinforce lecture concepts by performing power converter experiments in the laboratory sessions. In our approach we adopted the principles of the problem-learning methodology. With this approach, students can develop confidence and the abilities needed in project design, as well as in their senior capstone design courses. The design experience develops the students' lifelong learning skills, self-evaluations, self-discovery, and peer instruction in the design's creation, critique, and justification. Students learn to understand the manufacturer data sheets, application notes, and technical manuals. The experience, which would be difficult to complete individually, gives the students a sense of satisfaction and the accomplishment that is often lacking in many engineering courses, using traditional teaching approaches. Furthermore, the design experience motivates student learning and develops skills required in industry. The use of computer software packages for simulation and modeling is encouraged throughout the course to verify concepts and compare the results, giving the students additional skills necessary in the present day industrial settings. The inclusion of renewable energy power electronics projects was considered very favorable by the students. Our approach in teaching power electronics received a positive response from them as well. In general, students feel they learn more effectively in a practice-oriented project-based course focusing on the applications of power electronics in the new emerging technologies of renewable energy. This project-based approach in teaching power electronics gained significant interests thorough a survey piloted in fall 2008, and also received favorable comments from the Industrial Advisory Committee of our department.

Future work will involve the addition of new projects, especially for grid-integrated wind and solar energy conversion systems, fuel cells and hybrid power systems. A longer term goal is the development of the e-learning version of the course and laboratory experiments, as well to fully integrate the electric machines, drives, power electronics and renewable energy laboratories in single system. In this way at the same workstations the students will perform the experiments required in all these courses in setting much more with the one found in industry.

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