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The Power of Undergraduate Research

Implementing an undergraduate research program to help ensure availability of qualified professionals to face today's energy challenges

ELECTRIC ENERGY SYSTEMS HAVE EXPERIENCED DRAMATIC CHANGES IN THE LAST 20 years. There is a need at all levels in industry, from large utilities to small consulting firms, for prepared professionals that can deal with energy issues at the utility side as well as at the customer side. It is important to improve the education of engineers in energy-related areas in order to ensure a pool of qualified professionals that will face today's energy challenges. Nevertheless, there has been a dangerous trend at U.S. universities to reduce or even close power engineering programs.

Over the years, the power engineering program at the University of Puerto Rico-Mayagüez (UPRM) has prepared engineers to deal successfully with industry challenges. An important strategy in a recent power engineering curriculum renovation has been to give a more prominent role to undergraduate research. A new Energy Systems Instrumentation Laboratory (ESIL) has been established at UPRM to

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support the integration of undergraduate research within the power curriculum.

ESIL is both a physical space and a teaching philosophy. It occupies two laboratory spaces at the Electrical and Computer Engineering (ECE) Department, and it is also an environment where students are active participants in the learning process. Undergraduate research projects at ESIL provide an opportunity for students to study in detail theoretical concepts presented in class, improve their understanding of engineering principles and applications, and explore the frontiers of knowledge in power engineering. The ESIL also fosters the integration of teaching and research and the development of new teaching methods for the improvement of undergraduate education. This is done by adapting the results from projects to courses in the form of demonstrations and laboratory practices. Research projects also provide measurable outcomes of student work that can be used to comply with new ABET accreditation criteria.

A Look at How the University of Puerto Rico-Mayagüez Does It

UPRM and the ECE Department

UPRM was founded in 1911 as a land-grant college under the provisions of the Morrill-Nelson Act. Today, over 800 professors and researchers, 1,200 supporting staff, and approximately 12,000 students are part of UPRM's academic community. The institution is fully accredited by the Middle State Association of Schools and Colleges, of which it has been a member since 1946. UPRM is among the top 15 institutions in the nation in undergraduate engineering enrollment. Over 4,600 students register each year in the university's engineering programs. UPRM is the largest source of Hispanic engineering graduates in the nation. The university graduates 700 engineers per year, or 25% of all Hispanic engineers nationwide. There are six engineering degrees offered: chemical, civil, computer, electrical, industrial, and mechanical engineering.

The Department of Electrical Engineering was founded in 1928. The electrical engineering master of science program was established in 1967, the computer engineering program (CpE) was added in 1981, the master's program in CpE in 1995, and a Ph.D. in computing and information sciences and engineering started in 2002. The electrical engineering program has been accredited by ABET since 1960 and the CpE program has been accredited since 1994. The ECE Department presently has 50 full-time faculty members, over 1,300 undergraduate students (including 500 computer engineering majors), and over 100 graduate students (www.ece.uprm.edu). The bachelor's degree is a five-year, 165 credit-hour program. There are five areas of specialization in electrical engineering: applied electromagnetic, control, communications, electronics, and power engineering.

Power Engineering

Contrary to the national trend of reduced programs, UPRM has a strong undergraduate power engineering program in terms of number of professors and students. Ten professors teach power engineering courses to 200 students each semester. Over 30 students graduate each year with a power engineering minor (at least 19 credits in power engineering courses). Although power electronics has been part of the power engineering curriculum at UPRM for over 17 years, two formal tracks were created after a program revision: power electronics and power systems. Table 1 lists UPRM's power undergraduate courses.

Role of Undergraduate Research

Undergraduate research projects enrich a student's education, preparing her/him for graduate school or the workforce. Through undergraduate research, students actively participate in the solution of engineering problems, learn how engineering theory is applied to solve problems, work side by side with faculty and graduate students, and improve their communication skills. Faculty members get a chance to influence to a higher degree the careers of students, encouraging them to excel in their jobs or to continue graduate studies. Undergraduate research is also a way for faculty to integrate research and teaching, a model proposed to balance the many duties professors have.

Undergraduate research has been an important component of the ECE curriculum for many years. The ECE Department has successfully administered the industrial affiliates program (IAP) for 14 years. This program supports undergraduate research projects in which students work closely with a faculty mentor to solve an engineering problem or improve/develop modeling tools. Industrial sponsors have a chance to evaluate the projects during the annual IAP meeting, in which students present the results and findings of

table 1. Undergraduate courses in power engineering at the University of Puerto Rico-Mayagüez.

Course	*Title*
INEL 4103	Electrical Systems Analysis III
INEL 4405	Electric Machines
INEL 4406	Electric Machines Laboratory
INEL 4407	Electrical Systems Design I
INEL 4408	Electrical Systems Design II
INEL 4409	Illumination Engineering
INEL 4415	Power System Analysis
INEL 4416	Power Electronics
INEL 4995	Professional Practice
INEL 4998	Undergraduate Research
INEL 5406	Transmission and Distribution Systems
INEL 5407	Computer Aided Power System Design
INEL 5408	Electric Motor Control
INEL 5415	Protection Design for Electrical Systems
INEL 5495	Design Projects in Power Systems
INEL 5496	Design Projects in Power Electronics
INEL 5995	Special Topics in Electrical Engineering

their work (www.ece.uprm.edu/~iap). This is a very valuable experience for students, professors, and industry. Besides the IAP program, the NSF/Puerto Rico LS-Alliance for Minority Participation (AMP) offers scholarships to undergraduate students working in research projects. Students can also receive up to six credits for the undergraduate research course (INEL 4998 in Table 1). Power engineering undergraduate projects have been sponsored by both IAP and AMP.

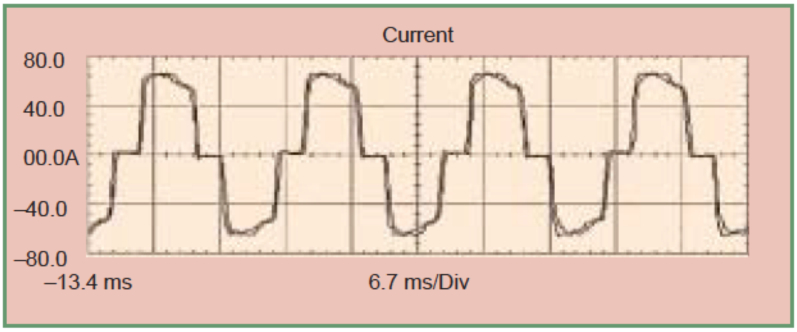

figure 1. Typical current waveform at computer area.

In power engineering, ESIL provides resources for undergraduate students to engage in research. ESIL was created through an NSF grant for course, curriculum, and laboratory improvement (CCLI). It combines the resources of an energy systems undergraduate laboratory (improved through a PECASE award) and a new capstone design laboratory. To broaden the impact of ESIL and ensure sustainability beyond the CCLI project duration, various collaborators have been identified for undergraduate research. UPRM's IAP (www.ece.uprm.edu/~iap) and PR-LSAMP also support undergraduate research projects at ESIL. Important support for undergraduate research projects in power engineering comes from current NSF-funded research projects in power quality and power electronics. Besides ESIL, undergraduate research is also carried out using the experimental and research facilities of the Electric Energy Processing Systems Laboratory (E^2PSyL).

Undergraduate research is also sponsored by the NSF's Engineering Research Center for Power Electronics Systems (CPES). UPRM-CPES was the first NSF ERC at the University of Puerto Rico. CPES is a consortium of universities led by Virginia Tech that includes as core partners UPRM, RPI, University of Wisconsin-Madison, and North Carolina A&T (www.cpes.vt.edu). CPES has played a key role in supporting power electronics activities at UPRM for the last five years. These activities have been a driving force for change in the areas of academic revision of curriculum, collaboration with industry, teaching, and research resources. UPRM participation in CPES has provided resources for undergraduate research projects in electric drives, thermal modeling of power electronics circuits, and chaos applications. Some of these projects are described next.

Projects in Power Quality

The multidisciplinary nature of power quality presents an opportunity to integrate various aspects of energy research and to renovate power engineering education in view of new challenges that exist in electric energy systems worldwide.

Student interest in power engineering has risen by incorporating undergraduate students in power quality research projects at UPRM. Furthermore, power quality can also be used to better integrate power electronics to classic power systems topics within the power curriculum. This approach can be adapted at other institutions as a way to deal with the limited number of courses usually available for power engineering.

Harmonics in Computer Loads

UPRM's first power quality group was composed of six undergraduate students working on the project "Harmonics in Computer Loads." Dr. O'Neill-Carrillo was the project advisor. The main objective was to determine harmonic pollution from computer loads at UPRM's ECE Building and provide recommendations on ways to improve power quality at the building.

The first phase included several seminars on power quality and power electronics to acquaint students with the theory. Next, a thorough literature review on power quality monitoring and modeling of computer loads and power electronics loads was performed. The third phase involved selection of areas within the ECE Building for the power quality survey or audit. The main computer area of the building, with over 80 computers and five servers, was selected. The facility is connected to the substation transformer through a UPS. Measurements were taken before and after the UPS, at all three phases and at individual loads. Figure 1 shows a typical single-phase current waveforms for the computer room. Figure 2 shows the current THD calculation from the Fluke 43. Average values between 20 and 40% were obtained for current THD, whereas values between 1 and 3% were obtained for voltage THD. Students developed MATLAB programs to determine THD from voltage and current measurements, and the results agreed with the instrument's computations. The main findings on that area included the existence of a neutral to ground voltage at the UPS, as well as the presence of harmonic currents at the secondary side of the transformer, which could shorten the life of the transformer. The group also performed other PQ surveys.

The power quality groups submitted the following recommendations to the ECE Department administration: avoid series distribution panels, PQ survey before installing new loads, isolate problematic and sensitive loads, rearrange branch circuits to improve balance, eliminate shared neutrals, use K-rated transformers and install harmonics filters when-

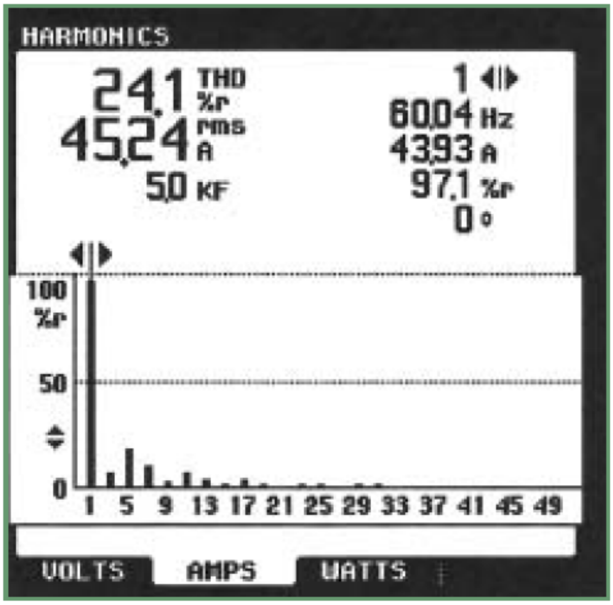

figure 2. Current THD obtained from instrument.

ever possible, conduct further studies of ground connections. The group also wrote a report; gave two formal, oral presentations; and had a paper included in a conference proceeding based on their work. The students agreed that the project helped them develop power quality survey skills; improve technical writing, presentation, and teamwork skills; and learn about instruments and software commonly used in industry for power measurements.

Simulation and Analysis of Power Quality Events

The emphasis of this project was on the prediction of low power quality by modeling the load and its interaction with the electrical system to which it is connected. Five undergraduate students developed a software environment to determine the power quality impact on current and future equipment using well-known software packages. Models were validated using actual electrical system measurements taken at UPRM's ECE Department. Figure 3 shows sample results from the simulations carried out in this project. The group wrote progress and final reports, delivered two formal, oral presentations, and had its work published in a conference proceeding.

Projects in Power Electronics

Electrothermal Models of Power Electronic Modules

This project dealt with the control and data for thermal models of power electronics modules. The system consisted of a computer-based data acquisition system based on Lab Windows-CVI from National Instruments with digital multimeters and recorders. Undergraduate students worked in the development of the system that calibrates and controls the testbed during experimentation. Data acquired includes temperature at different points acquired using thermocouples and voltages and currents at the module terminals. Communication between instruments and the computer is based on the GPIB protocol. Programs for calibration and transient data recording were developed. Results of the tests are compared with electrothermal models of power modules being developed at UPRM in collaboration with the National Institute for Standards and Technology (NIST). Figure 3 shows some results of comparison between transient temperature measurements and model prediction. Results from this project will be adapted for use in classes at ESIL. One undergraduate student participated in this project, which was funded by CPES and received support from NIST. The student presented her work at several meetings, had her work published, and is currently a graduate student in one of CPES' core partner institutions.

Simulation of Power Electronics Systems

This project was the first stage in the effort to implement a software environment for power quality studies that includes the level of detail necessary to assess power electronics' impact in power systems. There are many simulations tools for power applications, but not many can support an interactive mode where outputs of one simulation serve as inputs to other simulation. In power systems, EMTP-type programs are commonly used for simulation and analysis. In power elec-

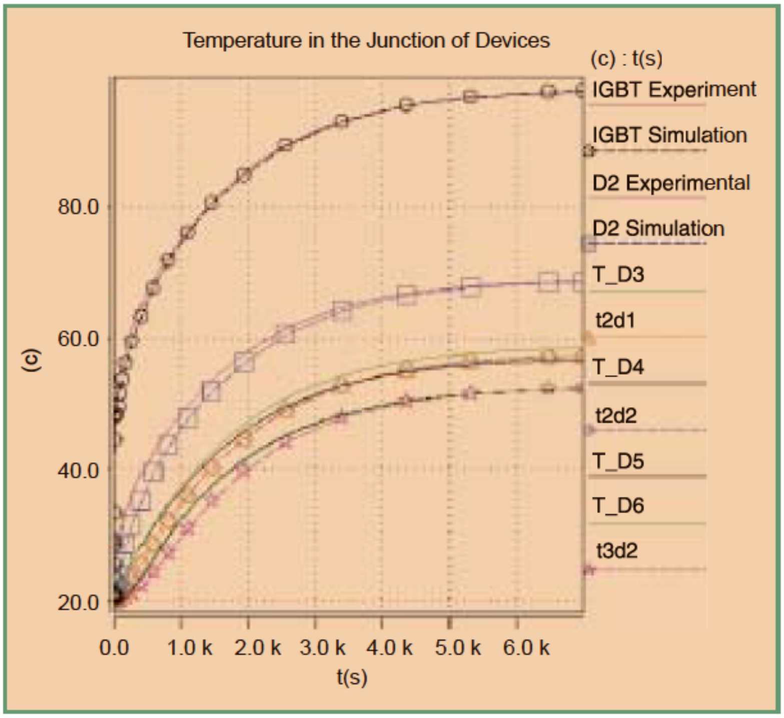

figure 3. Traditional protection scheme.

tronics, SPICE is commonly used, although complex simulations usually require a program such as SABER.

Three different options were considered to integrate SABER models into ATP simulations. The first option was to make a direct connection between SABER and ATP. A second option is to generate data in SABER for specified operating conditions, store it in memory, and retrieve it using ATP-MODELS. A third option would be a new environment or interface that links ATP and SABER. From all alternatives, students selected the Virtual Test Bed (VTB) created at the University of South Carolina (USC) as an environment where both programs can be connected. VTB provides a new high-level interface or environment for simulation and virtual prototyping of power electronic systems. The main feature of VTB is that it can integrate models that have been created in different languages and environments like SPICE, ACSL, and SABER into one simulation environment. VTB combines system-level models and devices-level models. Figure 4 shows a sample simulation from VTB. An ongoing collaboration with USC is expected to yield a VTB interfacing module for ATP.

Power Electronics Devices for Power Quality Improvement

Power quality studies offer a way to integrate power systems and power electronics research projects at UPRM. Collaboration between these two areas has strengthened the power engineering program and energy systems research. One graduate student and two undergraduate students completed one such collaborative research project as part of a PQ graduate course. The students developed simulations for some of the devices studied: dynamic voltage restorers, filters, and other power quality conditioners. A power quality analysis of the output waveforms was performed, before and after using the power quality conditioning devices, using traditional indices such as THD and flicker factor. The students delivered four oral presentations, including one at a conference. The two undergraduate students in this project continued graduate studies at UPRM.

UPRM-CPES REU in Power Electronics

CPES was granted a Research Experience for Undergraduates (REU) Award by NSF. The project includes a joint Virginia Tech-UPRM eight-week summer research program. The main objectives of UPRM-REU program were to provide opportunities for non-CPES students to engage in research projects on power electronics, to foster graduate education in power electronics, and to expand CPES impact beyond UPRM. Two undergraduate students participated on two projects guided by a graduate student mentor and supervised by Dr. O'Neill-Carrillo. After a recruiting, selection, and planning period during Spring 2002, two students from the Polytechnic University of Puerto Rico (PUPR) in San Juan were selected for participation in the 2002 UPRM-REU. They both had taken power electronics, electromechanical energy conversion, and basic control theory.

An important part of the program was a seminar series on various technical and nontechnical topics, with an emphasis on power electronics. These seminars gave students the necessary background to work on their projects and better adjust to the demands of research activities. The topics included: research skills, electric drives, introduction to power quality, IPEM philosophy, career counseling on graduate studies, and communications skills.

The key aspect of the CPES REU program was the undergraduate research projects. A thorough literature review on power electronics modeling and simulation tools and other topics relevant to each project was completed. Theoretical studies were carried on, then modeling and simulation of systems followed. One of the projects dealt with *grid-tied inverters.* The student designed an inverter capable of interaction with the utility power system. The design work involved considering different power electronics devices for interconnection, adverse conditions regarding utility-interactive inverters, and some possible solutions. Interconnection requirements of distributed generators (DGs) with the utility system were also studied. A second project dealing with the design was a cascaded motion controller for a separately excited dc motor using the MATLAB/Simulink software. The performance of various controllers was compared and an analysis was done to compare both controllers. A challenge for this project was that the student had to learn drive theory within the eight-week program period. Both students improved significantly their ability to use SPICE, and they learned how to work with SABER. One of the students will continue graduate studies at UPRM.

Renewable Energy Sources

Another topic that merges power systems and power electronics is generation using alternate energy sources. A project in this area at UPRM consisted of studying ways to interconnect photovoltaic (PV) systems to the grid. Four undergraduate students worked in this research project. A small PV system was installed at the ESIL of the ECE Department. The system is capable of

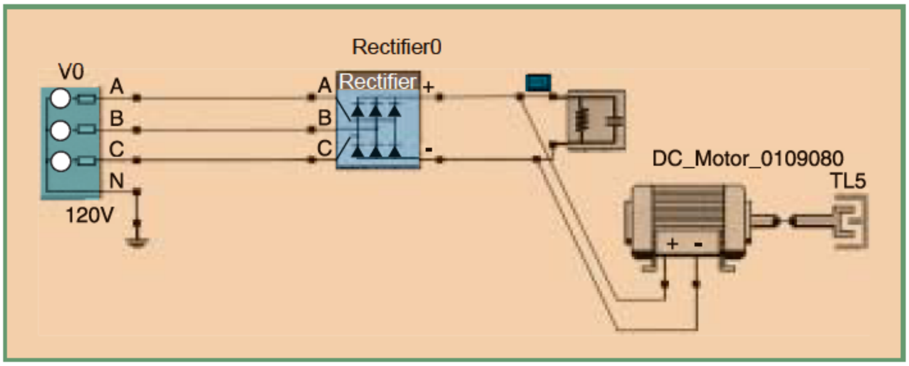

figure 4. VTB schematic.

Students actively participate in the solution of engineering problems, learn how engineering theory is applied to solve problems, and work side by side with faculty and graduate students.

stand-alone and utility connection. The system can provide up to 1.5 kW, 120 V, at 60 Hz, but the installed solar cell capacity is just 200 W. This mode of operation was used to acquaint the students with the operation and components of the system. Students completed a literature survey that included the studies of IEEE Standards 519 and 929. They studied the power quality and islanding concerns related to interconnecting PV systems. Students carried out computer simulations using SPICE. Students validated their simulations with actual measurements from the test PV system. There were two presentations related to this project, and one conference paper was published.

Research in Distributed Generation

Since distributed generation (DG) is close to load centers, it can be used to relieve capacity-challenged, aging transmission and distribution networks and increase power quality. However, DG can negatively impact the typical distribution network (DN) protection schemes. This undergraduate project had as an objective studying the impact of DG on distribution protection schemes.

Several simulations were developed and are used to illustrate the impact distributed generation can have on an electrical system. Two models were created, one using a load flow program, the other using ATP. The first model was based on an actual 11-bus 13.2-kV rural distribution feeder, which featured medium loading and long lines. The feeder features light commercial loads, a high number of light to heavy residential loads, and several industrial loads. To explore the impact the DG unit would have on short circuit currents, fault conditions were modeled in Figure 5. All of the faults simulated were completed in the base case, with no DG unit, and the improved

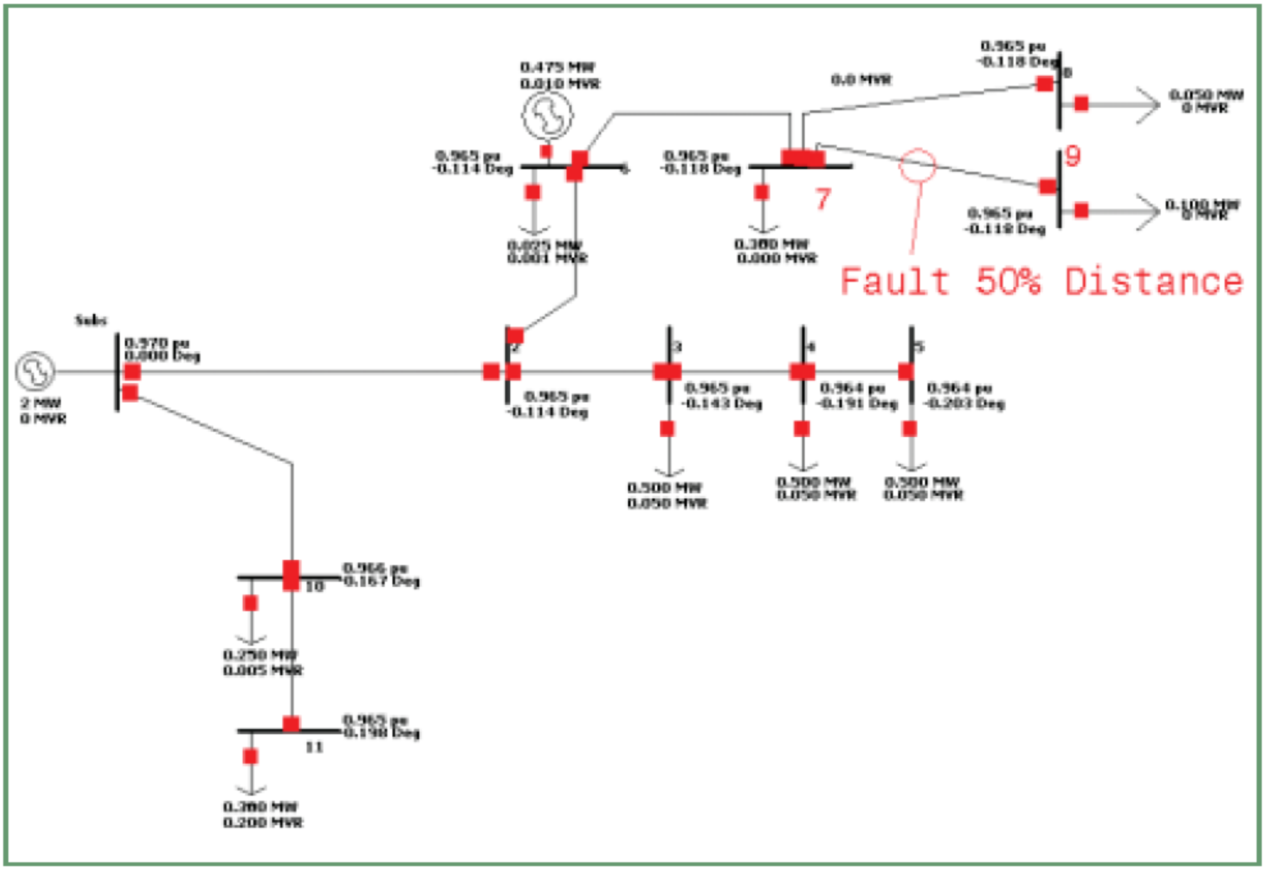

figure 5. Location of line-to-ground fault between buses 7 and 9.

case featuring the DG unit, and results were compared. Single-line to ground faults were simulated to ascertain the feeder's behavior to such condition with the DG unit installed. This kind of fault is the most common in rural feeders due to tree and/or animal contact with the lines. A fault was simulated at a 50% distance in the line connecting buses 7 and 9 as shown in Figure 5.

The second model was created on ATP, based on the 4.16-kV IEEE 13 bus test feeder reference system. Several modifications were made to the reference system for simpler implementation in ATP. One notable modification to the reference system is the addition of a simulated DG unit on one of the nodes. The ATP model recreates a single-line to ground fault in phase C. Simulated system tripping follows, including the DG unit disconnection, local node fuse action, and substation tripping. This work has yielded three oral presentations and two conference publications. The undergraduate student will continue graduate studies at UPRM in August 2003.

Undergraduate Research Impact on Education

Research projects can improve undergraduate education in power engineering by integrating research in the classroom. Research results can be used as examples or as in-class problems in power engineering courses. Another research/education activity is to integrate research tasks such as literature reviews and journal-style term papers into courses. Some undergraduate projects have been turned into lab exercises or class examples for use in other courses. Specific examples of the impact on education are presented next.

Design Course in Power Electronics

The creation of INEL 5496 ("Design Projects in Power Electronics") provided an advanced design course for undergraduates. A graduate student collaborated with Dr. O'Neill-Carrillo and Dr. K. Venkatesan in preparing the course material. During the first installment of the course in Spring 2002, students worked in teams of three to design various topologies for power supplies. Since then, students have also worked on motor drive designs and UPS systems. This course has also been influenced by research, since the Spring 2003 group is working on the design, simulation, fabrication, and test of a brushless commutator for permanent magnet dc motors. This converter will be used for a prototype magnetic levitation train being built at UPRM. Dr. Irizarry-Rivera is the faculty mentor for this group.

Development of Educational Tools

Other projects have had as the main objective the development of educational tools for power engineering courses. An example of educational projects was the development of virtual worlds to explore electric power grids and plants. In this project two undergraduate students participated in the design and implementation of two virtual worlds: a QuickTime VR model of a power plant, and a VRML model of a power grid (both used in electric power systems courses). The purpose of developing these educational aids was to provide an economical and accessible way to help students relate and differentiate the mathematical description of a device and its actual appearance. In a sense these aids provide a virtual laboratory experience. Dr. Irizarry-Rivera was the project advisor.

ABET

Increased opportunities for undergraduate research are meant to benefit students. Involving students in the learning process by making them active participants rather than passive observers transforms the classroom into a true learning environment. Undergraduate research was structured such that the power engineering curriculum could help meet new accreditation criteria. Thus, by implementing strategies to improve the quality of education, the power engineering faculty also supported the ECE program accreditation.

table 2. Survey on student perception of the learning experience.

Item / Scale	1	2	3	4	5
How much participating in the project helped in my learning and development concerning:					
Taking initiative and making decisions					
Capability for group work					
How to do a literature review					
Generating research questions from the literature review					
Knowledge of the state of the art in a particular area					
Skills in measurements and data collection					
Writing a report for the research project					
Communication skills					

Quantifying the Lessons Learned

An evaluation plan to assess the impact of research projects is being implemented. Two instruments will be used: An assessment instrument and/or approach to evaluate impact in improving student learning, and an instrument to assess student perception of their learning experience in undergraduate research. Table 2 shows a sample of one of the surveys developed for the project.

The instrument was tested with a group of undergraduate students performing research in the last two semesters. Initial results show that students feel that the research experience improved their technical background, communication skills, and ability to make decisions. Student participation in undergraduate projects has increased their research skills and their interest in power engineering. ESIL has enabled more students to participate in power engineering projects in power quality, renewable energy systems, distributed generation, and power electronics. Many of our students continue graduate studies either at UPRM or abroad.

The impact of ESIL can be assessed from student participation in research work (over 40 in the last four years) and the impact the laboratory has had on the curriculum. ESIL has had an impact on research training. ESIL's graduate teaching assistants expand their knowledge and experience of engineering education by being exposed to contemporary teaching techniques, both in content and format. ESIL has increased teaching resources for power engineering, which will translate into better course content and class time management. This will improve the quality of power engineering education, helping to ensure availability of qualified professionals to face today's energy challenges. The integration of research and education is also important for professors. They get a chance to train potential graduate students and practice the scholarship of integration and dissemination (present research work to a larger audience). An important lesson learned is that integrating research to the undergraduate curriculum increases student interest in power engineering as a career and for graduate studies. The multidisciplinary nature of power engineering problems and undergraduate student participation in research projects present an alternative to the education crisis in power engineering.

Acknowledgments

The contributions of over 40 undergraduate students who have participated in power engineering research projects at UPRM in the last four years are gratefully acknowledged. Support from the following NSF grants is also acknowledged: CCLI DUE-0088619, CAREER ECS-0134021, PECASE ECS-9702860, and Center for Power Electronics Systems (CPES) EEC-9731677.

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Biographies

Efraín O'Neill-Carrillo obtained a Ph.D. degree from Arizona State University. He is an associate professor and the power engineering coordinator at UPRM. Dr. O'Neill-Carrillo is the recipient of several NSF research grants including the Career Award. He is very active in education and outreach activities, from precollege students to continuing education for professional engineers.

Miguel Vélez-Reyes received his Ph.D. degree from MIT (1992) and is currently a professor at the UPRM ECE Department. He has held faculty internship positions with AT&T Bell Laboratories, Air Force Research Laboratories, and NASA Goddard Space Flight Center. He received the PECASE award from the White House in 1997 and the IEEE-PES Walter Fee award in 1998. His teaching and research interests are in the areas of modeling, estimation, system identification, and control systems. He has over 45 publications in journals and conference proceedings. He is the UPRM Campus Director for CPES.

Agustín Irizarry-Rivera is an associate professor of electrical engineering at UPRM. He attained a Ph.D. degree from Iowa State University. Dr. Irizarry-Rivera currently leads various research efforts in power engineering including UPRM's NSF/ONR EPNES project. He also has extensive administrative experience as associate director of electrical engineering and as assistant dean of academic affairs at UPRM.

Eddie Marrero is an assistant professor of social sciences at UPRM. He holds a Ph.D. in psychology from the Rio Piedras Campus of the UPR. Dr. Marrero is part of UPRM's Center for Applied Social Research and has extensive experience in assessment of educational activities. p&e