AC 2009-161: ENERGY MANAGEMENT AND RENEWABLE POWER DESIGN PROJECTS FROM A UNIVERSITY POWER GRID

Carl Spezia, Southern Illinois University, Carbondale

Carl J. Spezia is an Assistant Professor in the Electrical Engineering Technology Program located in the Department of Technology at Southern Illinois University Carbondale (SIUC). He joined the program in1998 as a Visiting Assistant Professor. He worked as a power systems engineer for electric utilities for eight years prior to seeking a career in higher education. He is a licensed professional engineer in Illinois. His industrial assignments included power system modeling, power systems protection, and substation design. He received his M.S. and Ph.D. from SIUC in 1991 and 2002 respectively. He teaches courses in electric power and machinery, industrial automation, and electric circuits. His research interests include power systems economics, power markets, and electric energy management.

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Abstract

Project-based learning is a recognized method for engaging students. Projects involving industrial power systems give students exposure to current methods and practices relevant to their future employment. Students benefit from the knowledge and experience of practicing engineers. Combining classroom instruction with a capstone design project reinforces key principles and gives students a practical application for their knowledge. This paper reports how electrical facilities of a university and personnel responsible for its design and maintenance became key partners in energy management and renewable power projects for a capstone senior design course. This paper documents grid operations, power plant efficiency, and energy cost control projects, focusing on a substation design for integrating a wind turbine into the university's grid. The project includes topics in power systems analysis using practical design methods. Effective collaboration among university service and academic units can enhance students' learning experiences.

I. Introduction

Project-based learning engages students and promotes a deeper understanding of technical content.[1,2] A senior capstone design course uses project-based learning to apply theory to practical situations. These course projects also strengthen project management skills such as team building, cost estimating, scheduling, and open-ended problem solving.[3] Industrial sponsorship of design projects introduces students to principles and methods used by practicing engineers.[4] Industrial sponsors benefit by having designs and prototypes developed at low cost. Developing and maintaining design project sponsors is critical for educators who wish to deliver challenging and technically relevant capstone design courses.

Finding relevant industrial power systems design and energy management projects is particularly important for two reasons. In the past fifteen years, the electric power industry underwent an economic restructuring that reduced the number of employed engineers. Engineering schools de-emphasized or eliminated power systems curriculum in response to reduced industrial demand. The electric power industry now faces an aging engineering workforce with a large number of individuals near retirement.[5] The current electric power engineering workforce must transfer practical knowledge to students and novice engineers before leaving the workforce so that the power grid can grow reliably.

Volatile electricity prices encourage firms to use energy efficiently and explore application of renewable sources such as wind and solar power. These are high growth areas where practicing engineers combine knowledge from many disciplines to complete projects.[6] Design teams benefit from interactions with engineers that have experience in these dynamic fields.

Local electric utilities and cooperatives currently provide the capstone design course, ECE495ab at Southern Illinois University Carbondale, with power systems projects. Industrial sponsors' headquarters are located at distance from the university, making these projects difficult to coordinate. Design teams and industrial representatives meet infrequently. In some cases, the only contact design teams have with project sponsors is telephone and e-mail. Design team work review is also done electronically. Lack of face-to-face interaction limits practical knowledge transfer from power engineers to team members.

Design course faculty overcame these limitations by developing a relationship with university engineers. These electrical engineers produce power distribution, energy efficiency, and renewable power projects that give students design experience. Having the industrial sponsor and design team co-located on campus increases personal interaction and facilitates transfer of technical data and practical knowledge. University engineering staff meets with design teams and guides them to a practical design. This paper examines factors that made this partnership possible and provides a list of projects showing their scope and content. The paper includes highlights of a recently completed power system design to demonstrate student performance and results.

II. Senior Design Course Structure

The senior design course at the university takes place over two semesters and provides a capstone experience to all engineering students. Its structure is similar to other universities' capstone design courses.[7,8,9] Student teams work on projects in a simulated design firm. Course objectives include: introducing students to project management techniques, mastering technical writing, and enhancing oral presentation skills. A faculty team representing electrical, mechanical, and civil engineering teaches the course and assesses student performance. Faculty solicits projects from sponsors, evaluates projects for fitness, presents vetted projects to students, and assigns students to their preferred projects. A faculty technical advisor mentors students. Students also obtain technical information from their sponsors. Project concepts derive from industry, engineering faculty, students, and other university units.

The outcome of the first semester is a project proposal. The course requires each team to research the technical background required for the design and define the work scope. In this part of the course, students acquire the necessary technical information to create designs. Course faculty, the faculty technical advisor, and project sponsors meet with design teams to review work throughout the semester. At the end of the first semester design teams submit project proposals to course faculty for assessment. The proposals include a literature review, a design basis, and a list of deliverables. Students also present project schedules and define individual task responsibilities in their proposals.

Teams produce designs in the second semester. Teams select appropriate equipment based on design calculations and standards. Design teams develop engineering drawings and prepare cost estimates for their projects. Some projects require a working prototype. Students document their projects with design reports. They present and defend their work before the course faculty, students, and project sponsors in formal oral presentations.

III. University Power Plant and Distribution System Overview

Plant Service Operations (PSO) handles all maintenance functions for the university, from grounds keeping to building operations. PSO works with university administration to develop long term plans and construction for campus. PSO employs skilled crafts and engineering personnel to support these functions. Plant Engineering Services (PES) is the design branch of PSO at the university.

Two electrical engineers provide electrical system design and maintenance support to PES. This staff initiates and implements projects that impact campus energy consumption such as LEED certification of buildings. They also study the campus electric distribution system and form plans to improve its efficiency and reliability. In this function, they examine campus load patterns and evaluate rate proposals from prospective energy suppliers to determine how to lower university energy costs.

PSO operates and maintains the university's steam plant and power distribution grid. The steam plant consists of three operating boilers: #3, a coal-fired stoker; #4 a natural gas fueled boiler; and #5, a circulating fluidized bed (CFB) boiler. Boilers #3 and #4 discharge steam directly into the campus header at 125 psig for distribution to campus buildings, where the steam provides heat. In summer, steam output drives chillers that cool campus buildings. Boiler #5 discharges steam at 675 psig to a back-pressure turbine driving a 3.5 MW generator. This generator produces electricity to offset utility costs.

The university campus connects to the local utility grid through a 12.47kV substation located near the steam plant. The steam plant structure also houses the electricity distribution feeders for all campus buildings. The distribution feeders consist of 12.47 kV and 4.16 kV cables located in tunnels beneath campus. These tunnels also house steam distribution piping. Distribution transformers located in campus buildings change the primary voltage levels to 480/277 and 208/120 V for consumer use.

University administration and PSO recognize environmental impact and economic benefits of renewable resources for electricity production. An external grant funded a 30 kW demonstration solar array that is connected to the university grid and monitored by PES personnel. PSO staff is evaluating the feasibility of a wind generator to augment current energy production from the back-pressure turbine.

IV. Engineering Design Partnership Development

The PES and engineering design course partners share a sense of mission. This mission is to provide the best possible educational experiences for the students. As with any successful partnership, both entities must realize benefits and make compromises for the relationship to work effectively. In this case, PES engineers, as members of the university community, are mentors and project sponsors, furthering the educational mission. In return, they receive the benefit of the students' project support and the personal satisfaction of helping develop engineering talent. Course faculty tap into a sustainable local source of energy and power-related projects for the capstone design course.

Several factors were critical in developing this relationship and can be used to replicate results at other institutions. Some factors are unique to this instance, but there are integral principles found here that are necessary in developing any relationship. These factors are:

1.) Open communication between PES engineering and engineering faculty,
2.) Mutual respect for the respective missions of PES and engineering faculty,
3.) Previous PES engineering staff experience in engineering design as students,
4.) PES engineering staff who are engineering college alumni,
5.) PES engineering staff desire to mentor and teach future engineers.

Items 1 and 2 must be present for any partnership to develop. One party must start a dialog for any relationship to begin. In this case, engineering faculty used a prior industrial relationship with a member of PES to start the dialog. The opening conversation made both parties aware of potential benefits and opportunities for sponsoring student design projects. Without pre-existing relationships, educators must identify and contact members of equivalent engineering units at their institution to explore possibilities for sponsorship and collaborative work.

Engineering educators and practicing engineers have different missions and goals. This is important to remember when developing design project sponsorships with any firm. PES engineers provide educational experiences as part of their mission, which makes design project development easier. PES staff is aware of student and course limitations. PES engineers work in conjunction with engineering and technology faculty who specialize in power systems to develop challenging projects that meet the needs of both parties. These interactions give PES staff access to faculty expertise and current research. Faculty members benefit from exposure to current industry trends and daily problems facing energy engineers.

Items 3 and 4 uniquely affected the development of the PES-engineering design relationship at the university, since both PES electrical engineers are alumni. These individuals wish to give back to the institution and lend their experience to develop future engineering talent. One individual also serves on the industrial advisory committee for the electrical engineering technology program within the college of engineering. In these capacities, PES staff contributes to the quality of engineering and technology graduates.

PES staff exhibits a high level of commitment to teaching and mentoring, item 5. This is critical in any design sponsor relationship and enhances student experiences. PES electrical engineers, with the approval of higher administration, consider the steam plant and power distribution grid to be a living laboratory where students can have an impact on the circumstances of their surroundings by reducing energy consumption and helping the university reduce operating costs.

V. Recent Collaborative Projects

PES projects for fall 2008-spring 2009 include design projects that include both mechanical and electrical engineering students. The aim is to improve energy efficiency of the campus steam plant, improve electrical grid capacity, and increase reliability.

Steam Plant Economic Dispatch
A design team of mechanical and electrical engineering students create models of campus boilers using steam plant data provided by PSO. The design team uses these models to determine the least-cost schedule of boiler operation over a range of electricity prices and fossil fuel costs.

Electricity Generation Expansion
The existing steam turbine/generator produces electricity based on #5 boiler steam output that varies with campus heating and cooling loads. This project examines the feasibility of retrofitting #5 boiler to produce full steam output and converting excess steam to electricity with a condensing turbine/generator. Students create a schematic design of the new system and determine economic value using campus operating data. This project requires a mechanical engineering design team.

First Contingency Outage Response for Electrical Distribution System
A team of electrical engineering students studies the impact of a single transformer fault on the campus 12.47/4.16 kV primary distribution system. Students model the distribution system from data provided by PSO and propose a protective relaying scheme. The project also requires students to develop an outage response plan that includes design of a mobile electrical substation for emergency service.

Control Design for Active KVAR Compensation of Campus Electric Load
Recently revised electric rates include significant charges for reactive power demand. A previous project proved the feasibility of fixed capacitor banks for reactive demand control. This project requires students to examine the effects of active control of reactive demand using an adjustable capacitor bank. A fully developed, cost-justified design with a working simulation results from this project.

These projects were offered to students during fall 2008. The following section highlights a completed project.

VI. Case Study-Alternate Campus Substation

A student team recently completed a PSO-sponsored project to design an alternate campus substation that increases distribution system capacity and accommodates a future wind generator connection. The project specification required a connection into two distribution systems owned by different companies at different voltage levels: 69 and 34.5 kV. The dual connection would maximize potential benefits from selling wind generator output in the open electricity market. These systems had to connect to the campus 12.47 kV grid. Fig. 1 shows a simplified one-line diagram of the resulting work[10].

Project specifications forbid simultaneous substation operation from both external sources. Since the most expensive design component was the substation transformer, the team selected a three-winding transformer for the substation. This is a novel design that was proposed by a team member who had seen a similar solution applied at an electric cooperative during a summer work experience.

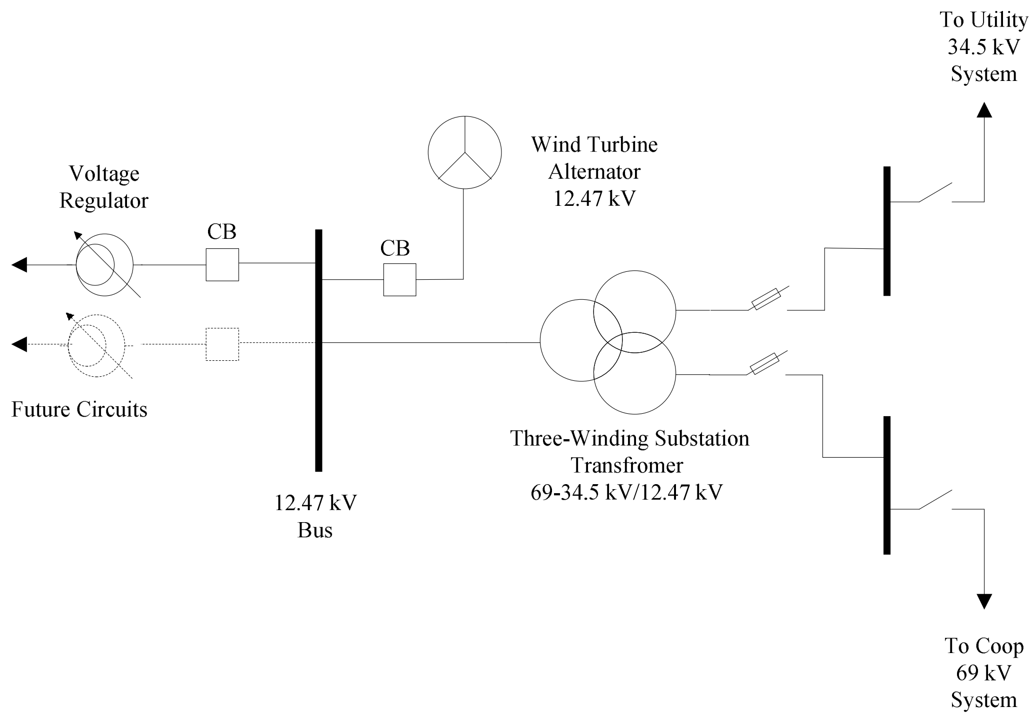

Fig. 1. Simplified One-Line Diagram of Alternative Campus Substation.

The team completed a systems level substation design that included grounding, protection, power metering, SCADA communication, and a control house. The team conducted load flow and short circuit studies using commercial software to determine the impact of the proposed substation on the interconnected utility systems. Fig. 2 shows the equivalent 69 kV system used to produce the fault analysis results shown in Tables 1 and 2[10].

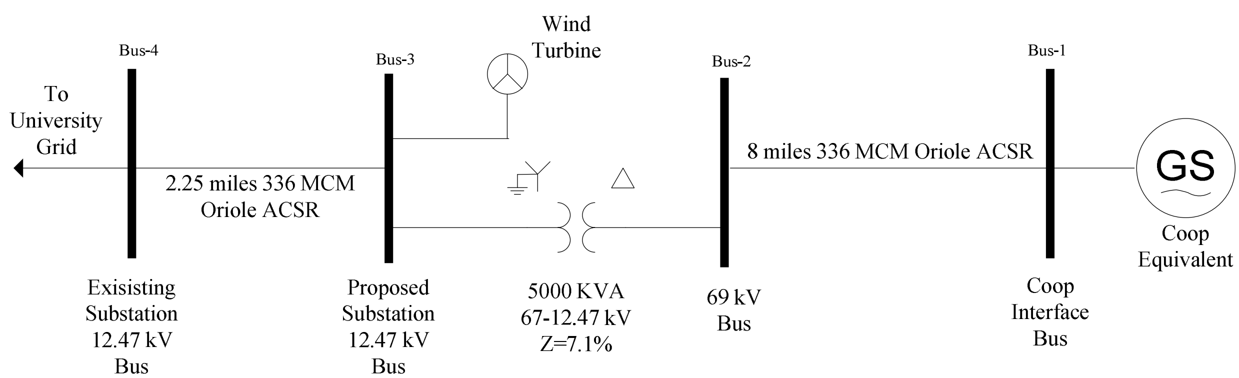

Fig. 2. 69 kV Short Circuit Study System Model.

The design team used these results to select protective relaying devices, to design the ground grid, and to determine breaker-interrupting duty. A similar study gives results for the 34.5 kV system.

Table 1. Three Phase Fault Analysis Results

3 PHASE Fault									
Bus Name	Bus kV	Sym Amps	X/R Ratio	NACD	Breaker Type	Int Time Cyc	Part Time Cyc	Bkr Duty Amps	Bkr Duty MVA
BUS-1	69.00	1031.5	7.06	0.811	Sym	5	3	1031.5	123
BUS-2	69.00	999.2	7.43	0.804	Sym	5	3	999.2	119
BUS-3	12.50	3377.3	18.42	0.561	Sym	5	3	3377.3	73
BUS-4	12.50	2733.0	7.78	0.561	Sym	5	3	2733.0	59

Table 2. Single Line-to-Ground Fault Analysis Results

S L-GND Fault									
Bus Name	Bus kV	Sym Amps	X/R Ratio	NACD	Breake r Type	Int Time Cyc	Part Time Cyc	Bkr Duty Amps	Bkr Duty MVA
BUS-1	69.00	973.0	5.48	0.860	Sym	5	3	973.0	116
BUS-2	69.00	899.7	5.59	0.854	Sym	5	3	899.7	108
BUS-3	12.50	3756.5	15.11	0.296	Sym	5	3	3756.5	81
BUS-4	12.50	2400.9	7.13	0.296	Sym	5	3	2400.9	52

The team measured soil resistance at the proposed site using a commercial ground resistivity meter implementing the Wenner four pin method.[11] They found an average test resistance value, R, of 10.738 Ω. Equation (1) converts this value into ground resistivity with a= pin spacing, and b= pin depth. The calculation found a soil resistivity of 65.93 Ω-m for the proposed site.

$$\rho_a = \frac{4\pi a R}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}} \ \Omega\text{-m} \qquad (1)$$

The team used the IEEE substation grounding standard to complete the ground grid design.[11] Short circuit studies found a maximum fault current of 19 kA at 12.47 kV. Using the computed resistivity and fault current, the team selected a 26.5x30 ft rectangular grid constructed of 250 MCM copper conductors with ¾ inch, 10 foot copper-coated ground rods. This grid connects to the power transformer and substation steel structures. It extends three feet beyond the substation fence.

The team selected high-voltage fuses based on short circuit study results to coordinate with 69 and 34.5 kV transmission protection schemes. The team selected fuses instead of circuit breakers to limit total project costs. Table 3 lists the fuse selections for both interconnections.

Table 3. High-Voltage Fuse Choices

Operating Voltage (kV)	Fuse Type	BIL (kV)	Continuous Amps
69	SMD	350	42 A
34.5	SMD	350	84 A

Three-phase circuit reclosers provide 12.47 kV feeder and wind turbine protection. These devices have adjustable tripping times that allow coordination with other university grid protection. The protective relaying consists of one SEL-351 differential current relay for wind turbine protection, one SEL-351 differential current relay for feeder protection, and a SEL-501 overcurrent relay providing low-side transformer protection.

The project required revenue metering for both 69 and 34.5 kV interconnections. The team selected revenue-class potential and current transformers (PTs and CTs) to scale primary voltages and currents to instrumentation values. The team computed PT and CT ratios based on a transformer power rating of 5 MVA. Table 4 lists these results. The team selected two GE Multilin EPM 9430 electronic power meters and data acquisition nodes to measure energy and power demand. The PTs' and CTs' connect 69 and 34.5 kV voltages and currents to these metering devices.

Table 4. Metering Transformer Ratios

Voltage	PT Ratio	CT Ratio
34.5 kV	300:1	100/200:5
69.0 kV	600:1	50/100:5

The team made extensive use of intelligent electronic devices (IEDs) in the design of the substation protection, metering, and SCADA systems. Figure 3 shows the communication system configuration and its integration into the protection and metering schemes.

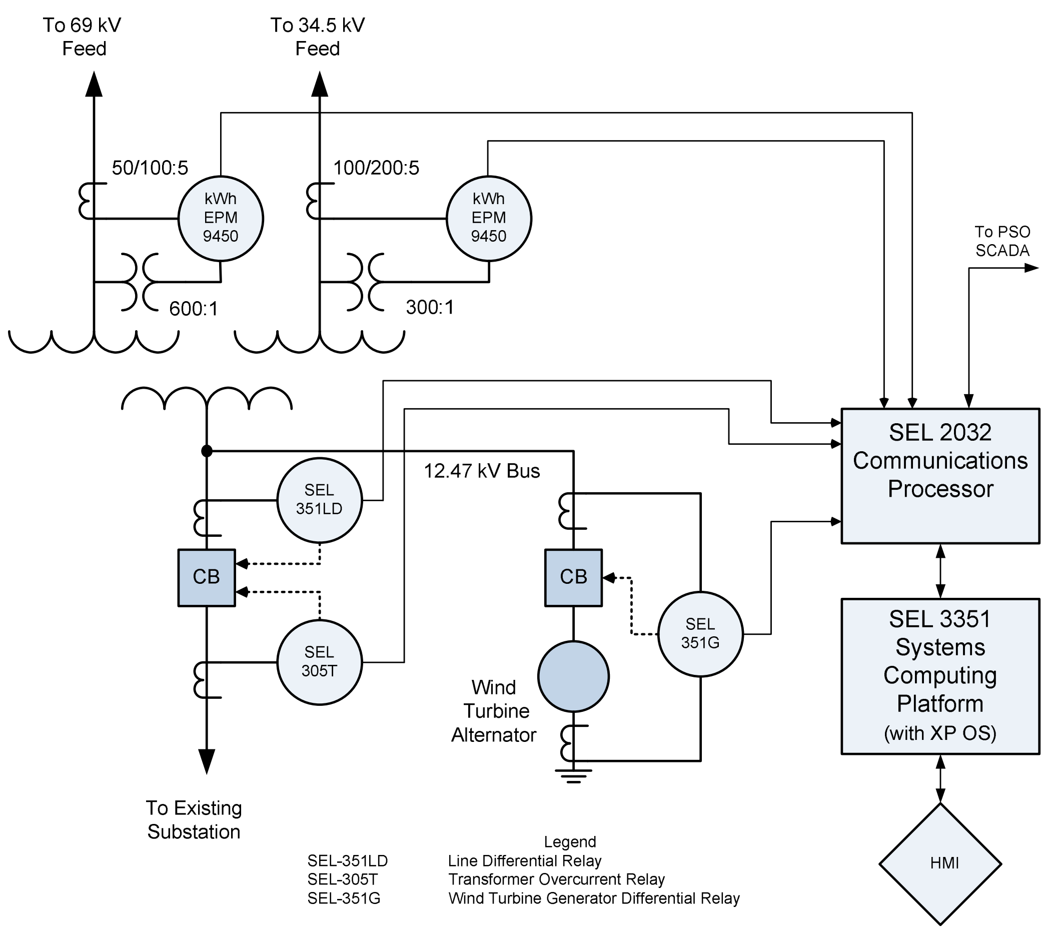

Fig. 3. Design One-Line Diagram Showing Communications Links.

The meters and protective relays communicate with university SCADA through a SEL 2032 communications processor. This processor moves information between IEDs and routes IED information to the PSO control center. This processor links the local line differential relay, SEL-351LD to its opposite terminal. An industrial PC, the SEL-3351, provides maintenance personnel with a local terminal for relay programming and data collection.

A metal control building houses all protection and communication equipment. Fig. 4 shows the control building plan view. The team selected a turn-key design that includes, HVAC, lightning, dc batteries, battery charger, and ac/dc distribution panels. This control house requires a suitable concrete foundation. Cable ducts and trenches in the substation yard route control cables to this control building where they terminate.

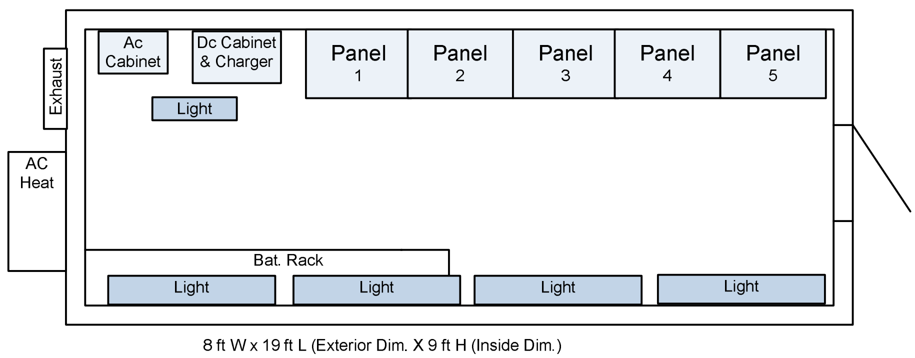

Fig. 4. Control Building Plan View.

The design team produced a cost estimate of their design using manufacturers' prices. Their estimated total cost was $972,997[10]. This cost is realistic and would be useful for budgeting. The design was acceptable to PES staff and course faculty. Future projects focus on wind turbine integration.

VII. Conclusion

Project-based learning in a capstone design course engages students and allows them to apply theoretical knowledge in a practical setting. This paper describes a collaborative effort to utilize the university power grid as a source of energy management and renewable power projects in a senior capstone course. It examined the development of relationships between university plant engineering staff and the engineering faculty, and identified five factors that allowed students to tap into staff expertise to enhance their course experience. These factors included: open communication between staff and faculty, respect for each party's mission at the institution, engineering staff that remembers their college design course experience and wants to mentor future engineers. As engineering college alumni, staff expressed the desire to engage with engineering faculty and students. On site interaction between staff and design teams aided in communicating specifications and allowing students greater access to practical knowledge and experience. The paper presented highlights of an alternative substation design to increase system capacity and interconnect a wind turbine. Student teams produced a system-level design and a cost estimate of the project that were acceptable to PES and course faculty. PES continues to offer project-based learning opportunities to engineering students because of successful examples such as this case study.

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