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A Power Systems Protection Teaching Laboratory for Undergraduate and Graduate Power Engineering Education

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A Power Systems Protection Teaching Laboratory for Undergraduate and Graduate Power Engineering Education

Abstract

The Electrical & Computer Engineering faculty at Portland State University has redesigned its BS- and MS-level electrical engineering power systems programs. This paper focuses on the development of a new education laboratory for the redesigned 400/500-level power system protection course. Specifically, we discuss the educational goals of the laboratory, the curriculum presented during the inaugural offering of the course, results from student surveys and our plans for refining the curriculum and expanding the laboratory.

Introduction

Motivated by the growing demand from the regional power industry for engineering graduates versed in power systems, as well as a need to provide continuing education opportunities for the local power engineering workforce, the Electrical & Computer Engineering faculty at Portland State University has redesigned its electrical engineering power systems emphasis programs at both the BS and MS levels. This paper focuses on the development of the education laboratory for the redesigned, 400/500-level power system protection course. The educational goals of the lab are to provide students with hands-on experience with industry protection equipment and software, enhance the classroom-based course curriculum, and acquaint students with industry standards and design practices. This paper discusses the design of the lab in detail, with an emphasis on the benefits of practical experience for students entering the electrical power industry workforce.

The Portland, OR, metropolitan area hosts numerous power-related entities, including around two dozen power engineering consultancies, two investor-owned utilities, two significant federal entities focused on hydropower and transmission, several power plant developers & operators, and a growing number of high-tech manufacturers and software companies focused on smart-grid products and services. In order to provide students with practical hands-on experiences in preparation for careers in the local power industry, we have designed the protection lab curriculum around using standard industry relays, software and test equipment. The purpose of the protection lab is to provide practical educational experiences for both working professionals who wish to enhance their engineering education, and more traditional full-time electrical engineering students.

The protection lab curriculum correlates with the weekly course lecture material. Students apply concepts discussed in lecture during laboratory experiments. Three teaching stations each include various electromechanical (EM) and digital relays, particularly over-current, distance, directional power and differential protection elements. Real-time and programmable automation controllers are also available for exploration. Each teaching station also includes fuse conductors and current transformers, important elements in protective relaying schemes. Students run experiments to identify fuse conductors through high current applications and examine waveform phenomena of saturated CT cores. Separately, EM relay and digital relay setting calculations and testing for different types of faults are performed. Using ASPEN and

ETAP system simulation software, students record and analyze information regarding system parameters under fault conditions for balanced three-phase faults, single-line faults and line-to-line faults for both radial and looped systems. Students use Matlab to write settings calculations, obtained in course lectures, to calculate relay settings, based on the software parameters. Students determine the accuracy of these calculations using relay testing equipment by performing fault simulation directly on the protective equipment. Students use ASPEN to coordinate actual protection schemes for radial and looped systems in order to explore relay coordination on multiple bus systems. These coordination tasks are balanced with direct relay assignments in order to keep labs at pace and in sync with lecture course material.

Motivation

The Pacific Northwest, particularly around Portland, OR, hosts a large and diverse power industry. The regional utilities, consultancies, federal entities, developers, manufacturers and engineering service firms, as well as companies within the high-tech cluster moving into the smart grid domain, represent a sizable fraction of the regional economy. Investment in new generation and transmission, innovations in communications and IT, and rapidly-decreasing prices for renewable resources are all contributing to the industry's growth.

The impending large-scale retirement of power engineers has long been forecast.[1,2] Several recent publications echo these projections for nation-wide, large-scale retirements from the power industry.[3,4] A 2011 survey by the Center for Energy Workforce Development (CEWD) projects a 38% turnover of engineers to occur between 2010 and 2015, with an additional 15% turnover in the ensuing five years, amounting to a need for nearly 15,000 replacements by 2020.[5] Regionally, three of the large employers of power engineers, Portland General Electric (PGE), PacifiCorp and the Bonneville Power Administration (BPA), project short-term, 2015-2020, retirement percentages on the order of 60% or greater (Table 1).[6, 7] In addition, technological, regulatory and political changes are resulting in increased investment in power systems planning and capital investment, further driving the demand for power engineers.

Table 1 Eligible and projected retirements of engineers in 2015 and 2020 at the two local investor owned utilities and BPA; data collected by the Oregon and SW Washington Energy Consortium, of which PGE, PacifiCorp and BPA are members.

	Current Workforce	**Eligible for retirement - 2015**	**Projected to Retire – 2015**	**Eligible for retirement – 2020**	**Projected to Retire - 2020**
PGE	95	44	68%	42	62%
PacifiCorp	200	27	80%	38	90%
BPA	450	144	66%	216	84%

Consequently, there is strong regional and national demand for power engineering graduates. In response to these opportunities and challenges, the ECE Department at Portland State University (PSU) has committed to developing educational pathways for electrical engineering students to become power engineers. PSU now offers two educational pathways leading to BS EE or MS ECE degrees with specializations in power engineering. The BS EE specialization consists of five upper-division power engineering courses, while the MS ECE specialization provides students the opportunity to take up to nine power-related engineering courses. An overlapping set of three 400/500-level courses encourages the BS EE graduates to matriculate into the MS

ECE power program.

These programs enhance professional opportunities for PSU graduates and attract new students who wish to expand their educational depth in power engineering. The program provides educational pathways for working professionals and develops a locally-educated engineering workforce in support of the regional power industry. The power system protection laboratory is a critical feature of these two programs.

In 2009, the IEEE Power System Relaying Committee (PSRC) established goals for protection laboratory curriculum.[8] Following the goal of the PSRC for universities to adopt an education model to successfully prepare students for industry, we established laboratory objectives for our protection laboratory to create a smooth transition from education to industry employment.[8,9,10] Power system protection is a rich and dense subject, and at PSU the course topics are covered during a fast-paced, ten week lecture series; time spent conducting laboratory experiments is therefore very important for emphasizing the real-world application of lecture material. The protection laboratory curriculum provides students an opportunity to apply theory learned in lecture to practical, industry-relevant issues, in turn preparing students for immediate employment in the electric power industry. The hands-on education with industry-standard equipment and simulation programs corresponds directly with the timeline of the lecture topics, thereby further enhancing the students' learning and career preparation.

Objectives of Laboratory

The main objective of this laboratory is to provide students with practical, hands-on experience applying concepts learned in lecture to standard industry protection equipment. To meet this objective, we looked to the colloquy of engineering educators who met in San Diego in 2002 to define 'The Fundamental Objectives of Engineering Instructional Laboratories.'[9,10] Developed for ABET with funding from the Sloan Foundation, we used these thirteen objectives as a guide when designing the PSU power system protection laboratory curriculum, with particular emphasis on the following:

Instrumentation (1)
Students investigate the characteristics and limitations of current transformers, and they make measurements of parameters for various electromechanical relays.

Models (2)
Students compare physical measurements with the corresponding theoretical models and evaluate the validity of theory learned in lecture. Students build software models to test protection coordination theory and compare results to what is expected during an actual event, determining the ability of the theory to predict real world behavior.

Experiment (3)
Weekly assignment descriptions clearly articulate test procedures, experiments and equipment. Students implement test procedures and experiments after a demonstration by the laboratory instructor.

Data Analysis (4)
Students collect, analyze and interpret data collected from testing equipment and software programs. They present these data through the written reports and through discussions with the lab instructors.

Design (5)
Students simulate power systems and coordination schemes using software tools according to specifications outlined in assignment instructions. They then test and debug simulation processes to determine design effectiveness.

Learn from Failure (6)
The laboratory assignments present many opportunities that test the students' ability to identify the reasons for unsuccessful outcomes, especially with regard to the labs covering the outmoded electromechanical industry equipment.

Psychomotor (8)
The laboratory assignments require students to properly select, analyze and operate laboratory equipment and assemble testing systems. We expect students to reference equipment data sheets and users manuals as means for teaching themselves how to operate test equipment and prepare elements for testing.

Safety (9)
Students must complete a quiz regarding electrical safety prior to using any energized lab equipment. Students apply lock-out, tag-out procedures when using energized sources. Each lab session reviews the safety procedures during the assignment introduction and overview prior to beginning experimentation.

Communication (10)
Strong communication skills are necessary for quality engineering in any discipline. The curriculum focuses on communication between team members and lab instructors. Each lab requires students to write a technical report covering experiment theory and results.

Teamwork (11)
Students work in teams of three while performing tasks in lab and synthesizing results for the written reports.

Laboratory Design

Each of the three teaching stations features a PC, a suite of digital and electromechanical relays, and testing equipment, thereby exposing students to both software and hardware tools. Within the ten week term, weekly assignments must be comprehensive, yet experiments must be able to be completed in the allotted three hour time frame to reasonably accommodate the schedules of working professionals. The laboratories expose students to the following topics:

Software
A steady state power system simulator, ASPEN, is used to determine system response and device

coordination using power flow studies and fault analysis.

Current Transformers
Two ratios of power metering CTs, 50:5 and 100:5, are used to demonstrate the difference in performance for difference ratios under different burdens and current in excess of nominal ratings.

Conductor Thermal Properties
Various gauges of bare copper wire are tested under a constant current to obtain the time-vs.-temperature curve.

Fuse Element Characteristics
Under increasing current, bare copper wire will be tested to obtain the time-vs.-current curve, as well as the minimum melting time and total clearing time of the fuse.

Electromechanical Relays
While the power grid is currently in the process of technological updates, the current equipment present in substations, especially many rural substations, is not expected to be replaced in the near future unless replacement is required due to functionality issues. The electromechanical equipment is considered outmoded for current industry applications, yet it serves an integral part in protection education because it is the foundation of the concepts digital relays operate upon. Electromechanical relays featured in the lab include the following:

- General Electric over-current relay IAC-53B (50,51)
- General Electric directional over-current relay JBC 51N (67N)
- ABB SC type auxiliary current relay
- ABB and Westinghouse SV type auxiliary current relay

Digital Relays
The digital relays used in lab represent common devices found in the power grid. The purpose of the digital relays is to familiarize students with common digital equipment used in protection design as well as to compare the operations of digital relays to the electromechanical devices. Digital relays featured in the lab include the following:

- SEL-311L Feeder Protection System
- SEL-351 Feeder Protection System
- SEL-551 Over-current/Reclosing Relay
- SEL-4000 Relay Test System

Application of Laboratory Curriculum

Software
The curriculum begins with orienting students to ASPEN software. Students create a simple case in ASPEN OneLiner, including positive-, negative- and zero-sequence impedances of lines and generators as well as proper transformer connections. Students run ASPEN Power Flow on a power system case and perform basic analysis of results, identifying the results of the power flow that have an influence in the fault study. Students perform a basic fault study, obtaining results for three phase, line-to-line, and single line-to-ground faults in the relevant parts of the

system. They then interpret the results, including automatic changes of the systems topology.

Students create radial power systems in ASPEN OneLiner containing the required information to conduct fault studies and over-current relay coordination where data of phase and ground OC relay elements are included in the model. Students design and test protection coordination systems. Students simulate faults and determine the behavior of over-current relay elements while performing a coordination study to determine the relay settings. The same tasks are performed for a looped power system model after lab exploration of digital over-current relays and directional over-current relays.

Thermal properties of Conduit and Fuse Elements
Students explore wire heating and fuse melting times, building temperature-vs.-time heating curves of a wire in free air and comparing the results of the experimental T(t) curve to ones predicted by the theoretical model using a Matlab or other scripting tool. The students then build an approximate time-vs.-current melting curve for a fuse and use the results to verify conductor material type based on the material behavior.

Electromechanical Relays
Students investigate auxiliary relays and EM relays, identifying the most relevant parts of the relay equipment. Students perform tests of electromechanical auxiliary relays to verify pick-up and time-current curves. Students are expected to explain the application of each part of EM relays, as well as test the accuracy of the pick-up current of the inverse-time relay element using relay testing equipment (Multi-Amp SR-51, Multi-Amp SR-76, Pulsar Universal Test System 10E3T3N) while constructing the time-current curve of the EM relay, comparing results with the characteristics given by the manufacture in the relay manual.

Digital Relays
Schweitzer Engineering Laboratories donation of three lab stations of equipment includes five of the most commonly implemented digital relays in transmission/distribution and substations. Experiments compare the operation of the digital models to the electromechanical models. Students explore the operation and processes of the micro-processor based digital operations.

Assessment

We assessed the course two ways, using weekly student surveys for each individual lab, and assessing the overall effectiveness of the lab goals using an end-of-term survey. This end-of-term survey assessed how well the course followed the emphasized goals of the laboratory course. Overall, student surveys show that the stated goals of the laboratory, as listed previously, were largely met. The two most requested means for course improvement were further refinement of lab instructions, and better equipment operation instruction and manuals. Comments from the students indicate that the lab was an important reinforcement mechanism for the lecture portion of the curriculum.

The student surveys revealed that the weakest lab experiment was the current transformer lab. In this lab, students construct a magnetization curve and observe CT behavior under different burden ratings. Students then analyze the magnetization curves by ramping the CT into saturation region in order to determine the experimental rated burden of the CT. They then compare this value to the nominal value given by the CT manufacturer. The execution of this lab was not completely successful for most groups due to difficulties demagnetizing the CTs after saturation during their very first saturation test. Therefore the measured current and voltage values reflected only the operation of the CT under core saturation. Different methods of demagnetizing were attempted, all with the same result. Further research with the CTs will be required to troubleshoot this issue so that the saturation test determining the magnetization curve will be effective. The labs that required use of the MultiAmp SR series relay testers received criticism regarding outdated equipment; two out of three units malfunctioned upon prolonged use, requiring frequent repair. This caused technical problems for the labs that require several minutes of continuous high current, particularly the fuse and CT labs.

The surveys revealed the strongest lab assignments were those focused on the electromechanical relays, due to their physical construction having direct application to theory presented in lecture. The students responded enthusiastically to these experiments; for many it was the first time they were exposed to industry-standard equipment. The electromechanical relay labs practically illustrated relay element concepts discussed in lecture. Specifically, these labs physically illustrated the practical difference and electrical separation of the instantaneous versus time delay elements and how these operations relate to coordination. The digital relay labs were also very successful, as students were able to compare tested results with calculated and simulated results.

In future, the order of the labs will be refined to keep pace with the course lecture topics. Students started the electromechanical overcurrent relays the week following their homework assignments and midterm over the subject. Having access and experience with the physical components of this material earlier in the term will be more beneficial to the student learning experience Also, the current transformer lab should be condensed and added to the auxiliary relay lab, which introduced the electromechanical relay principles as well as the relay testing equipment.

Development

To further utilize the digital relay equipment and to expand on course lecture material regarding distance protection and physical relay coordination, we will design two assignments for the Advanced Protection course. These lab exercises will require groups to program and coordinate digital relays, focusing specifically on the SEL-311L. Further, we plan to design and build a physical power system model in the power lab. This model will be similar to those found in industry for testing power system, with different length transmission lines, multiple buses, a variety of loads types and a fault simulator. We will incorporate both electromechanical and digital relays to provide system protection. Using this system, students will work with directly coordinating overcurrent, directional, distance, and differential relays. Design of this system is to begin during Spring 2013 with construction in Summer 2013.

Summary

The power systems protection laboratory is designed to directly apply theory learned in lecture to devices studied in lab, thereby deepening the students' knowledge of lecture theory while simultaneously preparing them for careers in the electric utility industry. In short, the hands-on experiences gained in the Portland State University power system protection lab directly prepare students for entry-level engineering positions. This practical experience for entry-level engineers is important in the current professional climate that is experiencing dwindling numbers of experienced power engineers. This is especially true for the Pacific Northwest, considering the large number of power-related employers, particularly in the Portland metropolitan area. The employment challenges faced by the regional electric utility industry present career opportunities for our graduates; providing educational pathways leading towards these careers is the principle objective of the redesigned BS EE and MS ECE power engineering programs at PSU. The power systems protection laboratory is a critical component of these programs, ensuring students gain industry-relevant, hands-on experience in preparation for their careers as the next generation of power engineers.

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