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Development of Laboratory Experiments for Protection and Communication in Radial and Bidirectional Power Systems

Mr. Kenan William Pretzer, California Polytechnic State University, San Luis Obispo

Kenan is an electrical engineering graduate student at Cal Poly San Luis Obispo, with a concentration in power systems. His thesis focuses on creating laboratory-scale power system protection experiments for students.

Dr. Taufik Taufik, California Polytechnic State University, San Luis Obispo

Dr. Taufik received his B.S. in Electrical Engineering with minor in Computer Science from Northern Arizona University in 1993, M.S. in Electrical Engineering from University of Illinois, Chicago in 1995, and Doctor of Engineering in Electrical Engineering from Cleveland State University in 1999. He joined the Electrical Engineering department at Cal Poly State University in 1999 where he is currently a tenured Professor. He is a Senior Member of IEEE and has done consulting work and has been employed by several companies including Capstone Microturbine, Rockwell Automation (Allen-Bradley), Picker International, Rantec, San Diego Gas & Electric, APD Semiconductor, Diodes Inc., Partoe Inc., and Enerpro.

Mr. Ali O. Shaban, California Polytechnic State University, San Luis Obispo
Ian Hellman-Wylie, Cal Poly, San Luis Obispo
Joey Navarro, Cal Poly SLO

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California Polytechnic State University

Abstract

Electrical utility companies increasingly rely upon automated fault detection to improve the integration and effectiveness of emerging smart grids. Responding to these circumstances in the rapidly-changing power industry, the electrical engineering department at Cal Poly State University in San Luis Obispo created Advanced Power Systems Initiatives to modernize the curriculum in its existing power electronic and power system courses. These initiatives expand the power systems laboratory curriculum to include a series of protection experiments. The newly-proposed set of laboratory experiments utilizes microprocessor-based protective relays to give students hands-on experience in power system protection. The experiments drive learning outcomes which incorporate the theory and practice necessary for technical careers in today's power industry. This paper presents an overview of the content and learning outcomes of the experiments, in addition to initial student performance.

Introduction

The growing density of distributed energy resources (DERs) in utility circuits calls for new considerations in circuit planning and operation[1]. Bidirectional power flow, in which customers with DERs send power back to the utility, requires protection schemes accounting for changing directions of load current. The time-varying power output of certain DERs (a function of weather conditions) requires that protection schemes also account for significant changes in load current over short time intervals. An emergence of micrograms operated on DERs also adds to the complexity[2], necessitating an acquisition of data fast enough to keep pace with real-time circuit performance. As technology continues to advance, microprocessor-based relays are increasingly utilized to meet these complex challenges faced by modern electrical utilities[3,4,5].

Faculty at Cal Poly recognize the growing role of microprocessor-based relays in the power industry. Operating under a "Learn by Doing" philosophy, Cal Poly prizes the active coordination of theoretical background knowledge with practical application. Three power systems analysis lecture courses and one power systems protection lecture course currently exist in conjunction with one laboratory course. A new set of proposed experiments expands the existing laboratory curriculum to include fault detection and isolation using microprocessor-based protective relays. Isolating faults using microprocessor-based relays gives students the opportunity to apply a knowledge of symmetrical components and relay coordination in a controlled environment that highlights key challenges faced in the power industry.

Learning Outcomes

Through the series of proposed experiments, students program microprocessor-based relays using RS-232 protocol. Students identify and set the communication parameters for each relay and apply them when connecting serially between a desktop computer and protection device.

Each procedure emphasizes the purpose and function of important relay settings by describing their effect on system performance. A special focus throughout the experiments on ANSI device numbers prepares students to quickly recognize common protection functionalities in literature and industry.

Students witness the effects of system protection in real time through special breaker box simulators, which combine manual and relay trip controls. These breakers enable safe initiation of fault conditions, allowing students to wire specific fault conditions into the circuit at each of the breaker boxes. This gives students hands-on exposure to the effect of fault conditions, in addition to seeing how and when protective relays respond to those conditions. Relay trip controls on the breakers highlight for students the working relationship between protective relays and circuit breakers.

The proposed experiments develop students' intuition regarding the path of current flow in radial and bidirectional circuit topologies. Exposing students to the concept of bidirectional power flow ties in with the challenge electrical utilities currently face from distributed energy resources which return power to the grid. In wiring up both types of topologies themselves, students explore available paths for current through the circuit. Figures 1 and 2 illustrate the proposed radial and bidirectional circuit topologies.

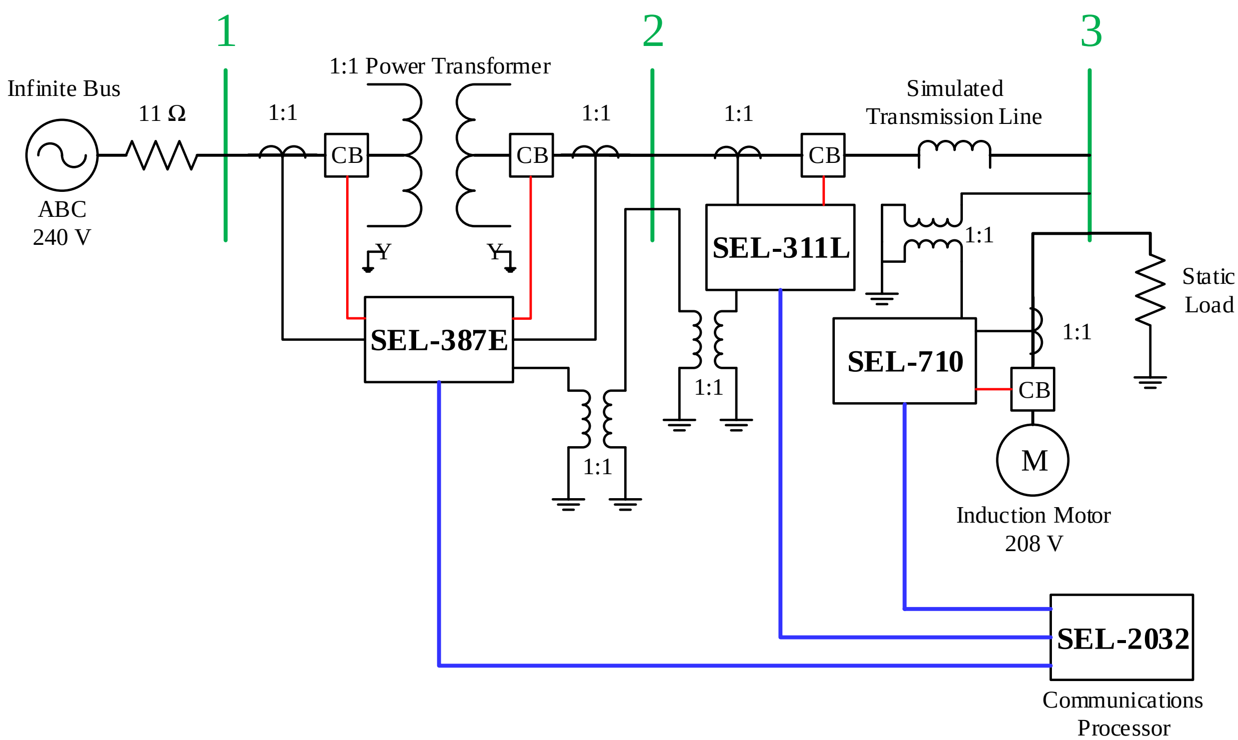

Figure 1. Radial Circuit Topology

Another practical lesson derives from a simplification in the laboratory setup. Due to the relatively low voltages and nominal load currents used (less than 500 V and 5 A), current transformers and potential transformers are not needed. Line currents directly flow into and out of each relay in the circuit. Removing this abstraction simplifies circuit construction, but necessitates phasing currents (switching input and output connections) for certain relays. This demonstrates to students the effect of current transformers on relay current measurements.

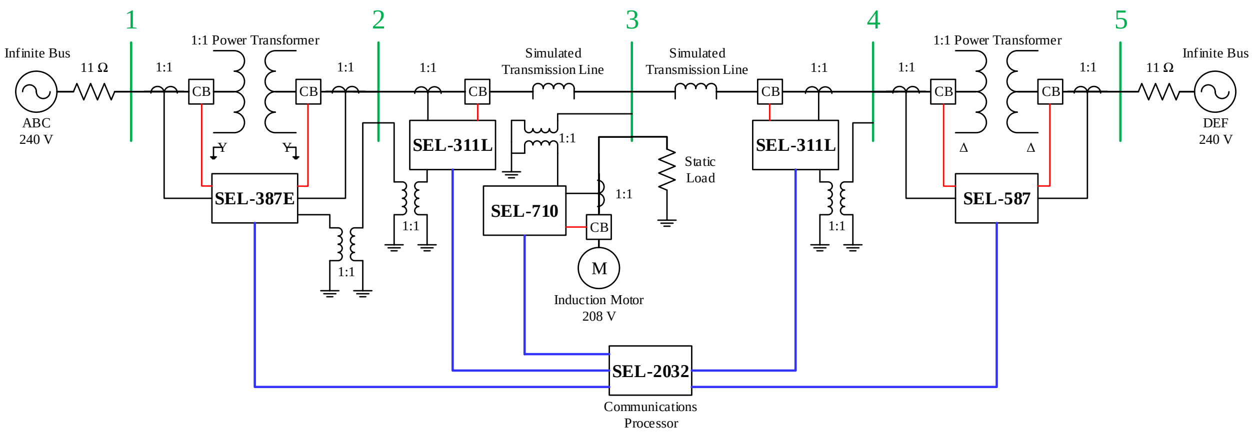

Figure 2. Bidirectional Circuit Topology

Incorporating materials covered in lecture courses, the experiments utilize symmetrical component calculations to predict how relays respond to fault conditions. Students confirm that the negative-sequence overcurrent settings suggested in the experiment procedures are appropriate for proper relay performance. Students also predict the speed with which overcurrent relays will respond to fault conditions using an inverse-time overcurrent coordination curve. Students then validate their relay response predictions by analyzing data taken during the experiment. Students download fault event files from each relay, identify the relevant relay trip signal for each fault event, and plot those digital signals on an oscillogram of the fault current data. This allows students to compare their predicted response times to the actual response time depicted on the oscillogram.

Content of Experiments

Each proposed experiment walks students through using a relay to detect fault conditions in a three-phase circuit and isolate the fault by tripping an appropriate circuit breaker. Students program the relay, construct a circuit, and collect requested data within a three-hour window. The lab manuals contain background information and any relevant calculations to be completed before starting the experiment, as well as discussion questions to be answered afterwards. Table 1 summarizes the learning outcomes for each of the proposed experiments.

Over the course of two experiments, students establish protection for a delta-delta power transformer using the SEL-587 differential relay. The first experiment introduces differential protection to detect faults in the primary and secondary transformer windings. Students then add phase and negative-sequence inverse-time overcurrent protection in a second experiment to detect faults downstream of the transformer.

Another set of two experiments reinforces the application of differential protection. Students protect a grounded wye-wye power transformer using the SEL-387E differential relay. Differential protection again guards against faults internal to the transformer, while overcurrent protection guards against downstream faults. Incorporating the SEL-387E relay into the curriculum in addition to the SEL-587 gives students experience implementing similar protection schemes through different relay settings.

Table 1: Content of Proposed Experiments

Lab	Device(s) Involved	Expected Learning Outcome(s)
1	SEL-587	Differential Protection
2	SEL-587	Inverse-Time Overcurrent Protection
3	SEL-387E	Differential Protection
4	SEL-387E	Inverse-Time Overcurrent Protection
5	SEL-710	Locked-Rotor and Definite-Time Overcurrent Protection
6	SEL-311L	Impedance Protection
7	SEL-311L	Inverse-Time Overcurrent Protection
8	SEL-311L, 387E, 710, 2032, 2407	Relay Coordination in Radial Circuit Topology
9	SEL-311L, 387E, 587, 710, 2032, 2407	Relay Coordination in Bidirectional Circuit Topology

Using the SEL-710, students provide two forms of protection for an induction motor. Locked-rotor protection incorporates the performance-monitoring capabilities of the SEL-710 based on programmed values of full-load motor current. Students test relay functionality by varying the external torque applied to a 208 V induction motor. The motor load current rises as the torque increases from no-load to locked-rotor conditions. In addition to monitoring motor characteristics, students detect faults at the motor terminals with definite-time overcurrent protection settings.

Students gain experience using impedance protection on a simulated transmission line by exploring capabilities of the SEL-311L line relay. This experiment leads students to characterize an inductive transmission line (modeled by discrete inductors) in terms of a standard conductor type and implement zones of protection appropriate to the perceived length of the line. Students also use phase and negative-sequence inverse-time overcurrent protection to detect faults along the line in a separate experiment.

Building on the operation of individual relays, two additional experiments introduce the importance of communication and coordination between devices in a power system. Students create a circuit combining components from the previous experiments and establish a communication link to each relay through an SEL-2032 communications processor. The communications processor distributes an IRIG-B timing signal to all relays from an SEL-2407 satellite-synchronized clock, which the relays use when time-stamping fault data. This allows students to access each individual relay through a single, intermediate point of connection. As part of the communication experiments, students also coordinate the performance of multiple overcurrent relays on the same circuit (Figure 3). Carefully choosing the time-dial setting for each device allows the relays to provide backup protection for each other, while minimizing the areas affected by various fault conditions.

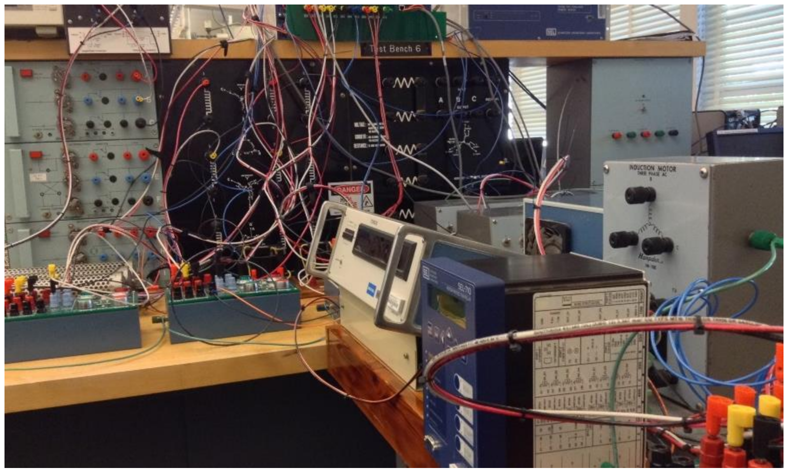

Figure 3. Laboratory Realization of Radial System

Initial Assessment

Assessment of student performance takes several forms. An instructor or assistant verifies circuit connections before students apply power and supervises them from a distance while they perform the procedure. Questions from the students during the procedure highlight points of confusion in the lab manual and suggest needed revisions. Each experiment contains postlab questions which highlight important concepts from each experiment and create connections between related topics. Students submit answers to these questions with their experimental data. Additionally, students respond to a short questionnaire asking for their opinions about the clarity, appropriateness, and effectiveness of each experiment.

Overall student feedback regarding the proposed experiments is positive. When asked about the relevance and effectiveness of the prelab and postlab sections in the procedures for the SEL-387E relay, one student responded, “The prelab was very helpful in understanding which breakers should trip and why they were tripping based on the relay settings.” He went on to state that “The postlab questions were very helpful in connecting the information from the prelab to the actual lab. The postlab helped explain some questions I had about why certain trips occurred during the procedure.” The prelab, postlab, and procedure in each experiment work together to effectively support the learning objectives defined at the top of each procedure.

Although students can benefit from the breadth of hands-on experience obtained in the procedures, they do perform the experiments slower than originally expected. Students require more time than anticipated to construct the circuits due to their unfamiliarity with the equipment. For this reason, the content in early experiments was spread over multiple lab sessions to facilitate a smoother introduction to the curriculum.

Conclusion

Throughout this set of proposed experiments, students program a variety of microprocessor-based relays and analyze fault data from relay-generated event files. Students coordinate relays in both radial and bidirectional circuit topologies, demonstrating primary and secondary protection functionality across each circuit. Proposed experiments resulting from the Cal Poly Advanced Power Systems Initiatives engage power systems students with hands-on curriculum, giving them practical experience in preparation for careers in the power industry.

Responding to the rate at which students completed the initial experiment, the proposed curriculum divides expected learning outcomes over a larger number of lab sessions. This enables students to focus more effectively on a smaller number of objectives in each experiment. Future assessment aims to gauge the long-term growth in comfortability students have with programming additional microprocessor-based relays.

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