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Development of Laboratory Experiments for Protection and Automation in Microgrid Power Systems

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California Polytechnic State University

Abstract

This project establishes practical laboratory coursework facilitating students to operate, coordinate, and integrate microprocessor protective relays in a low-voltage three-phase microgrid system. Three laboratory experiments are developed to serve as the laboratory component to an existing power system protection lecture course. The laboratory coursework development is part of the Cal Poly electrical engineering department's Advanced Power Systems Initiatives, which aim to modernize power engineering curriculum to more effectively educate power students and prepare them for the rapidly changing power industry. The experiments focus on auto-synchronization of synchronous generators to the utility, synchronous generator loss of field protection, and load shedding while the system is islanded. Using automation and control techniques, students have the opportunity to learn various power system protection schemes, as well as familiarize themselves with the communication and coordination of industry-standard power system protection equipment. Learning outcomes are formulated based on the desirable skills students should attain from components that make up the microgrid system. These include for examples relay programming, oscillogram interpretation, and setting up the proper generator connection. Further detailed descriptions of the three experiments along with their learning outcomes and assessment methods will be presented in this paper. Initial results of testing the experiments will also be described, along with challenges and lessons learned in the development of the laboratory coursework.

Introduction

While multiple definitions of microgrids exist, this paper defines them as "a locally controlled grouping of electricity sources and loads that normally operate connected to and synchronous with the traditional centralized grid (megagrid), but can disconnect and function as an autonomous electrical island if physical and/or economic conditions dictate"[1]. Microgrids address many problems that a centralized grid proposes, primarily by its ability to disconnect from the grid in the event of a disturbance[2,3]. This allows universities, businesses, military bases, and cities to have complete isolation and independence from the grid in the presence of faults on the main grid. Local generation and consumption also increase energy efficiency and decrease loss[1]. Although microgrids have existed for many years, microprocessor relay technology has spurred advanced communication and decision making within the microgrid system. When a microgrid system is islanded, frequency stability becomes an important factor in maintaining its reliability. Microprocessor relays placed throughout the system can provide standard protection against faults and gather information such as frequency. The relays send this information to a central communications processor, where decisions dictate load shedding to balance generation with consumption while maintaining the system's frequency. These technological advances coupled with government regulations to decrease negative environmental impact drive utilities toward viewing microgrids as a solution to handling decentralized energy resources on the grid. According to a survey conducted by Utility Dive, 35% of utilities plan to either develop, own, or operate a microgrid within the next five years[4]. Figure 1 illustrates the full breakdown of utilities' plans to build microgrids, showing a stark contrast between those with upcoming plans and those without plans. While some utilities lack plans to develop microgrids, their increasing prominence makes them an important fixture in grid infrastructure.

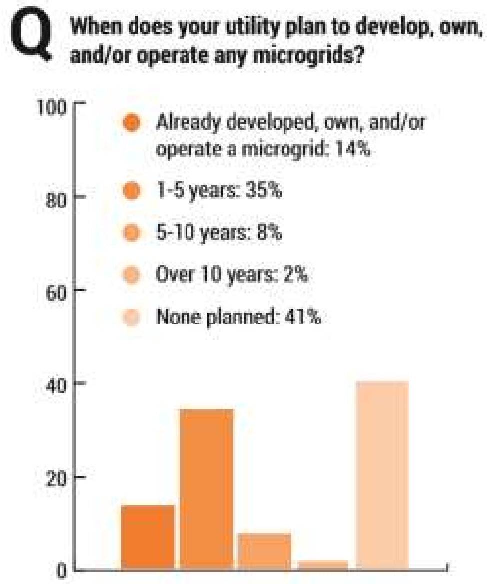

Figure 1: Utility Involvement in microgrids[2]

Although the power industry adopts the advanced technology of microgrids into their infrastructure, universities have fallen behind. Universities primarily teach electric machines and power system analysis with the assumption that the grid remains largely electro-mechanically controlled. This results from a lack of modern power systems equipment and accompanying laboratory material to teach its use. The protective relays in laboratories typically don't utilize microprocessors, making modern control and protection schemes hard to teach. While the industry has adopted new technologies to address problems associated with centralized generation, a new wave of electrical engineers lacks the knowledge to interact with and understand the modernized grid.

Faculty at Cal Poly recognize the need for teaching students the modern power systems concepts that are propagating throughout the industry. Coupled with Cal Poly State University's "Learn By Doing" approach, faculty in the electrical engineering department proposed a new, modern laboratory course to support the theory that is currently taught in its advanced lecture courses. Eight lecture courses and three laboratory courses covering power systems topics are currently taught at Cal Poly, but none address the prevalence of microprocessor relays. The existing lecture courses are three quarter units each if paired with a one unit lab, and four quarter units if taught without an accompanying lab section. Of the current lecture and laboratory courses covering power systems topics, only one lecture and one lab are required for EE students to take; the remaining courses are technical electives that span both undergraduate and graduate courses. All courses at Cal Poly are taught in an eleven week quarter, and all electrical engineering laboratories are completed in groups of two to three students. The proposed new laboratory course replaces one unit in an existing graduate level electrical engineering elective course that typically has between fifteen and twenty students. Pre-requisites for the course include two classes in basic power system analysis. The proposed laboratory course includes multiple fault protection experiments using microprocessor relays in a radial and bidirectional system as described in a previous work[5]. This paper expands on those experiments and instead focuses on teaching control and automation topics within a microgrid system. The intention is to enforce theoretical concepts of synchronization, frequency stability, and generator protection schemes with microprocessor relays commonly used in industry today.

Learning Outcomes

A series of experiments guide students through programming microprocessor relays using RS-232 protocol. Students select and set communication parameters for the relays, computer, and centralized communications processor. Students gain experience writing automation programs for a Real Time Automation Controller. Once the experiment is performed, students learn to export data from relays and analyze oscillograms relating to the task performed by the relay.

Students gain intuition regarding the relationship between frequency and power through system islanding. The relationship between synchronous generator voltage and reactive power is demonstrated by adding inductive loads to the system. Students observe the benefits of centralized control in a power system as it increases system reliability through automation. Figure 2 illustrates the proposed microgrid system and shows the relationship between the centralized controller, relays, utility, and synchronous generators. Figure 2 expands upon the original design as described in the previous work[5].

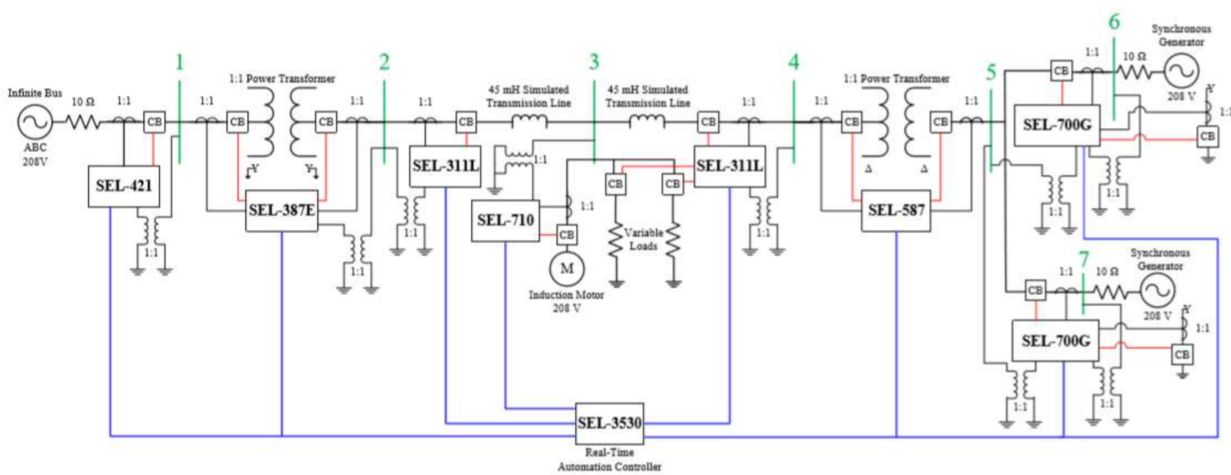

Figure 2: Proposed Microgrid System

The experiments teach students the specific purpose and function of each individual relay used. ANSI device numbers are highlighted throughout the experiment, and the broader context of a single microprocessor relay's capabilities are taught using the relay's settings interface.

Students gain exposure to real time system protection and automation. The relationship between relays and breakers is reinforced by physically wiring the input and output contacts of the relay to the breaker.

Interaction with a bidirectional power system develops students' knowledge of current flow in a non-radial system. Additionally, the bidirectional system exposes students to the modern challenges utilities face from distributed energy resources. Physical wiring of the system, an example of which is shown in Figure 3 and Figure 4, helps students identify direction of current flow. Current transformers and voltage transformers are not needed since the system voltage is 208VAC, making current and voltage relay measurements more understandable to the student.

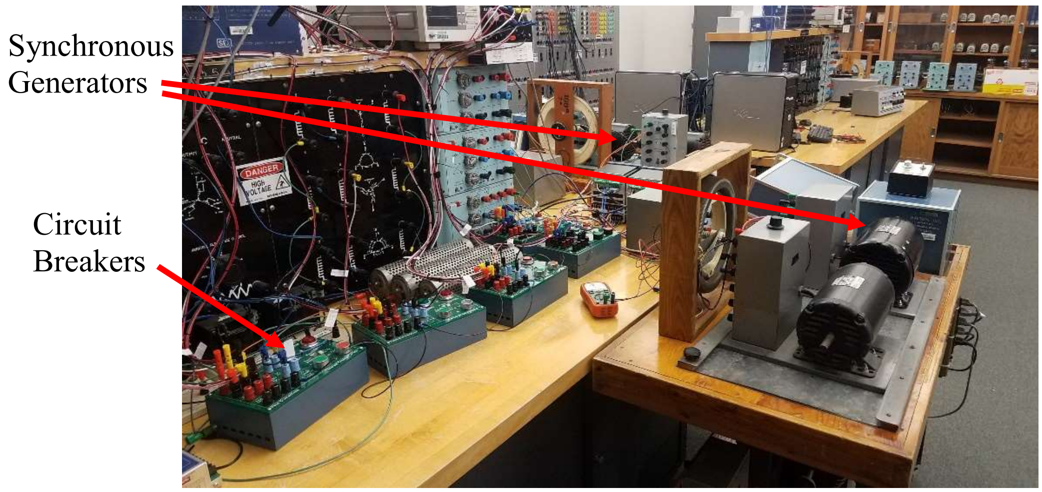

Figure 3: Laboratory Realization of Microgrid System - Generator side

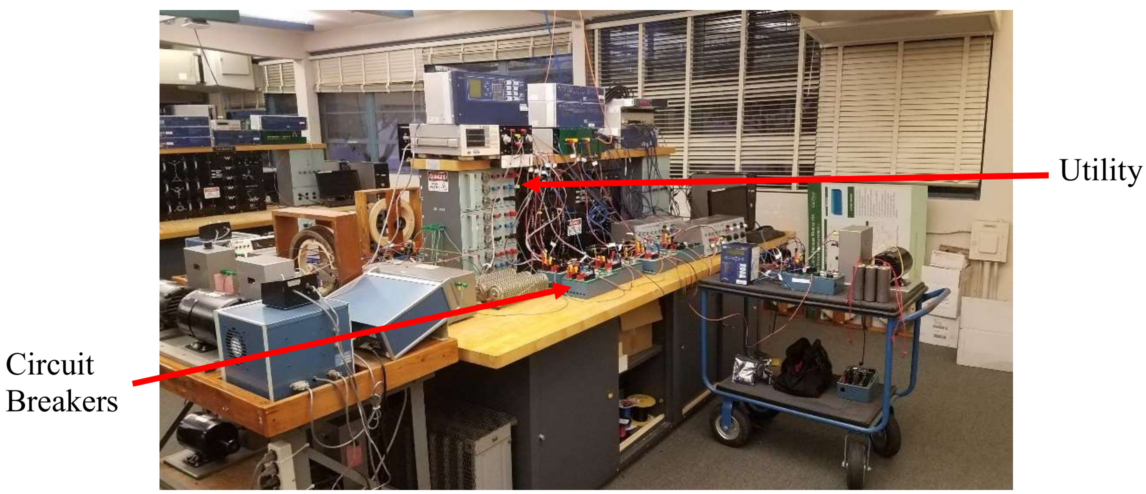

Figure 4: Laboratory Realization of Microgrid System - Utility side

The experiments incorporate lecture material by utilizing loss of field protection, synchronism-checks, and load shedding to validate theory. Physical interaction with the system reinforces key concepts taught in lecture that are important to the viability of the power industry today.

Content of Experiments

Each proposed experiment requires students to use a relay to detect either fault conditions or proper synchronism conditions in a three-phase circuit, and trip or close the appropriate circuit breaker. Within a three-hour lab period, students program the relay, build the required circuit, and collect all requested data. Background information and relevant equations are provided before starting the experiment. Additionally, calculations to be completed before the experiment are included, as well as discussion questions to be answered after completion. As part of each experiment, students analyze oscillogram data read from the relay and overlay it with the digital signals triggered by the specific event being studied in the experiment. Student learning outcomes for each proposed experiment are summarized in Table 1.

One experiment teaches the concept of the synchronism-check element using the SEL-700G. Voltage from the utility is distributed through the system and stops at the open circuit breaker connecting the generator to the system. Students set multiple parameters including maximum slip, voltage window, and percent voltage difference to instruct the relay when to close the circuit. Students must measure physical voltage quantities at the open circuit breaker bus and compare to theoretical values. Once settings are determined, students must adjust generator frequency and voltage to match the utility and trigger safe circuit breaker closure.

Another experiment uses the SEL-700G for a different purpose: generator loss of field protection. In this experiment, students use the mho characteristic to determine when the machine ceases to act as a synchronous generator. Students must compare nominal values to experimental values and set the parameters of the relay to trip the breaker appropriately. Students also test their settings by switching the generator field winding from synchronous run to induction start.

Integrating the SEL-700G from the previous two experiments, a third experiment has students use the SEL-3530 Real Time Automation Controller (RTAC) to preserve system frequency stability during islanding. Students modify a basic RTAC program that sheds static loads if the system frequency drops below the acceptable limit. Students use the measured frequency of the SEL-700G as an input that determines whether the RTAC issues a command for load shedding to the 311L. For simplicity, the 311L is strictly used as a trigger to open the circuit breaker and does not provide additional protection features in this experiment.

Table 1: Content of Proposed Experiments

Lab	Device(s) involved	Expected Learning Outcome(s)
1	SEL-700G	• Identify requirements for successful synchronization • Implement synchronism-check element • Interpret synchronization report and develop recommendations to improve synchronism results
2	SEL-700G	• Identify requirements to protect a generator from loss of field • Implement loss of field protection • Interpret oscillogram results and develop recommendations to improve protection scheme
3	SEL-3530, SEL 700G, SEL 311L	• Identify requirements to maintain system frequency • Implement an automated load shedding system • Analyze system frequency performance for different load and power profiles

Initial Assessment

Student assessment takes place during the lab (instructor verifying circuit and supervising from a distance). Postlab questions included at the end of each experiment reinforce important concepts. To complete the lab, students must submit answers to the postlab questions. Additionally, students are asked to respond to a short survey regarding the effectiveness and clarity of the experiments.

Initial student feedback regarding the experiments is positive. After performing the SEL-700G synchronism experiment, one student remarked that "the function and operation of the synchronism-check is much more clear now." Regarding the effectiveness of the postlab, he stated "the comparison to the relay settings help demonstrate how the settings affect performance". When asked about the effectiveness of the background information and prelab, he further stated that the "background information is helpful in understanding the requirements for synchronization." The background, prelab, postlab, and procedure in each experiment work together to accomplish the learning objectives stated in Table 1.

Since students completed the experiments in approximately two hours, a second portion to the procedure was added. Using one student's suggestion to have "students change one of the relay settings" after running the initial experiment, students now collect data for two different relay settings groups, further reinforcing the effect of the settings on system performance.

Conclusion

This set of proposed experiments provides students with an introduction to programming microprocessor relays and teaches the fundamentals of relay-generated event file analysis. Students automate a basic microgrid system and learn the basics of automated synchronization and generator loss of field protection. Proposed experiments resulting from the Cal Poly Advanced Power Systems Initiatives provide students with a hands-on learning opportunity that teaches modern protection and automation techniques to prepare students for careers in the power industry.

Because students complete the experiments relatively quickly, the proposed curriculum adds a second section of settings and data collection. This reinforces the purpose of individual relay settings and clearly shows their impact on system performance. Future assessment aims to measure long-term growth of student ability to program additional microprocessor relays.

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