Cal Poly EE 518

Electric Power Protection

Laboratory

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EE 462 Senior Design Report

In Partial Fulfillment

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Bachelors of Science in Electrical Engineering

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Abstract

Facing a rapidly-changing power industry, the electrical engineering department at Cal Poly San Luis Obispo proposed Advanced Power Systems Initiatives to better prepare its students for entering the power industry. These initiatives call for the creation of a new laboratory curriculum that utilizes microprocessor-based relays to reinforce the fundamental concepts of power system protection.

The electric power protection laboratory (EPPL) senior project is the validation of lab manuals written for the planned EE-518 power system protections laboratory looking to be offered in Spring 2020 alongside the current lecture class under the same designation. This report evaluates the lab manual, verifies SEL relay settings, updates experiment requirements and resources, and provides feedback on improving the coursework. The microgrid integrates photovoltaics, real time simulation, and power system protection devices ensuring the future EE 518 laboratory will provide hands-on experience with power system components and operation. The experiments expose students to the capabilities of industry-standard microprocessor-based relays through hands-on procedures that demonstrate common power system protection schemes. Relays studied in this project support transformer, transmission line, and induction motor protection.

This senior project and the Cal Poly microgrid project as a whole was created as an initiative by the power engineering faculty and electrical engineering department to provide additional lab course for students concentrating in power engineering.

Dedicated to those passionate about pursuing careers in Protections Engineering,

and to our families and loved ones.

Acknowledgements

We would like to thank Dr. Majid Poshtan for his support in conceiving and inspiring us to work with him on building the Power Protections lab. We are thankful to have learned from his genuine love for the material and his students. His many intuitive analogies were helpful with clarifying ideas complex ideas, and his stories from his life were always a welcome break from the stresses of senior project.

We would also like to thank Cal Poly Alumnus Eric Osborn, Matthew Guevara, Nicole Rexwinkel, Nathan Martinez, and Kenan Pretzer as well as Do Vo for being the students who developed the microgrid. Without their earlier work, the protections lab would not have come to fruition. Thank you to SEL employees Hank Nurse and Arpit Reja for instructing the SEL workshop at Cal Poly. Their teachings inspired the microgrid team to develop a unique digital systems lab using SEL-AMS.

Thank you to the PES representatives for being very considerate on allowing us to utilize the club room for our senior project. Thank you for being understanding on the transition as well as for being good friends towards us.

Special thanks to Rob Randle and Jaime Carmo for their support of our efforts. No matter our requests or problems they were extremely helpful and patient in getting the lab room configured exactly the way we needed.

Lastly, thank you to the entire microgrid team for supporting the power systems protection lab. Special thanks to Dr. Ali Shaban, Dr. Taufik, Dr. Ahmad Nafisi, and Dr. Ali Deghan for the feedback on the experimental demonstrations and the respect they displayed when critiquing our project. Thank you to the student members Patricia Liu, Jesus Morales, Virginia Yan, and JR Rancines for their dedication towards the microgrid team and their efforts on their respectful microgrid projects.

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List of Abbreviations

EPPL - Electric Power Protection Laboratory
SEL - Schweitzer Engineering Laboratories
AMS - Adaptive Multichannel Source
CB - Circuit Breaker
OC - Overcurrent
RTS - Relay Test System

Chapter 1: Introduction

1.1 Introduction

The Electric Power System Protection Student Laboratory (EPPL) is a laboratory course designed to provide Cal Poly students with hands-on experience in power system analysis and protection using microprocessor-based relays. The lab provides a platform for laboratory coursework in the fundamentals of fault protection, relay settings, and relay coordination. Students apply these fundamentals of protection theory to detect faults in transformers, transmission lines, and induction motors in radial and systems using microprocessor relays and other devices produced by Schweitzer Engineering Laboratories, Inc. The lab focuses on microprocessor-based relays in order to prepare students for an electric power industry that is experiencing a rapid shift towards automation and intelligent protection schemes where advanced multifunction protection and metering devices are quickly becoming the norm.

In light of this shift, the lab gives students the opportunity to become familiar with the capabilities of these intelligent electronic devices through exercises in relay programming and logic, event reporting and analysis, fault detection and clearing, relay-operated circuit breakers, and communication-based protection schemes, all in the context of modern microprocessor relays.

1.2 Project Background

There have been over 2,000 California fires in the span of three and a half years from 2016 to 2019. These fires resulted from California's three main utility companies: PG&E, SCE, and SDGE. Pacific Gas & Electric has reported approximately 1,552 equipment-related fires as of June 2014, through the end of 2017 [1]. Southern California Edison, an electrical provider for more than 15 million customers, reported about 347 fires [1]. Lastly, San Diego Gas and Electric disclosed 115 fires during the same time [1]. The damages from the fires have caused these utility companies to pay large fines related to electric safety violations. This includes PG&E paying at least $8.3 million in property damage in addition to SCE paying at least $15 million.

Power system protection is important to providers and customers alike. Protection systems on high power equipment is extremely necessary and successful implementation can mean the difference between a fault causing a momentary power outage for a neighborhood, versus starting a wildfire that causes millions or billions of dollars worth of damage, lost productivity, and human lives. These protective elements, called relays, measure frequency, current, and voltage and look for anomalous events such as voltage or frequency dips or current spikes that would signify a fault within the protected element. When such a fault is detected these relays activate circuit breakers that open the line and prevent further power transfer through the element. A common example of a fault event is a tree limb coming in contact with a power line and causing a fault to ground. When this occurs there is a spike in fault current down a distribution line which is measured by the relay, which can then tell the circuit breaker to open the line and prevent damage to what impacted the line as well as prevent further damage to the line.

Figure 1.1: *Example fault in a power line detectable through the use of relays*[2]

Providers aim to utilize the full potential of power system protection theory to implement protection schemes that are selective, secure, and reliable. Protection schemes that are selective ensure the minimum amount of equipment is removed from a power system while isolating the faulted components. Protective schemes that are secure ensure that protective equipment does not trip under normal operating conditions. Protective schemes that are reliable ensure components are protected by more than one relay so that in the event of a primary relay failure, components within the power system are still protected though backup relays.

The power systems within this project are transformers, simulated transmission lines, and induction motors, all of which would require protective relays in case of anomalous system operation or electrical fault. All relays used within this project were developed by Schweitzer Engineering Laboratories (SEL). Transformers utilize the SEL-387 and SEL-587 relays to protect them. Transmission lines use the SEL-311L relays for their protection. And finally, the induction motor is protected by the SEL-710 relay. These relays are coordinated within this project to maximize the selectivity, security, and reliability of the complete protection scheme.

Chapter 2: Project Description

2.1 Approach

Our approach to this project was to have physical and digital lab benches. The physical benches would display the protection of different power system components for experimentation and testing. The digital benches would allow the student to simulate digitally what was tested physically.

Room 101 in the EE building only has three functioning 3-phase power benches so the benches were designed for three common power system components: transmission lines, transformers, and motors. These components would be protected by the SEL-311L, SEL-587, SEL-710 respectively.

The digital benches would showcase the SEL-relay testing system (RTS). This testing system is composed of an SEL-AMS and any SEL relay in the -300 or -500 series. This component of the lab will also allow students to become familiar with different SEL software: AcSELerator, SEL-5401, and Synchrowave.

2.2 Deliverables

1. 3 Physical Lab Benches
    a. Equipped with 3-Phase Power
    b. One each: SEL-311L, SEL-587, SEL-710
    c. Dual monitor computer setups
2. 8 Relay Testing Stations
    a. Equipped with SEL-AMS
    b. Testable relays: SEL-311L, SEL-387E, SEL-587
    c. Dual monitor computer setups
3. EE518 Lab Manual
    a. Physical experiments
        i. SEL-311L transmission line protection
        ii. SEL-387E/587 transformer protection
        iii. SEL-710 motor protection

b. Digital experiments
   i. System OC: 311L, 387E, 587
   ii. System Differential: 387E, 587
   iii. Settings OC: 311L, 387E, 587
   iv. Settings Differential: 387E, 587
4. Educational Resources
   a. Youtube video series

Chapter 3: Customer Needs, Requirements, and Cost

3.1 Market Research

Currently, the Electrical Engineering department only offers a single Power Systems Lab course (EE-444) which contains only a single experiment dedicated to basic protective relay operation and relay coordination using electromechanical relays [3]. This experiment is meant as an introductory foundation into protection engineering. In the utility industry this is a huge component of what engineers work on in providing reliable power in the grid. This single experiment falls short of being an introductory in hands on protection engineering as it deals only with relay coordination, and does not use relay-operated circuit breakers to clear faults, which is the most critical part of protection engineering. Secondly, while electromechanical relays are still used in industry due to their reliability, simplicity of operation, and installation decades ago, they are being replaced by microprocessor-based solid-state relays, which have become ubiquitous in industry. This shortfall in protection curriculum is unacceptable at Cal Poly where the university prides itself on a learn by doing atmosphere. Practical, learn by doing, experience with these devices is critical for new protection engineers, since they will be using them extensively in their careers.

EPPL fills this gap by providing a tested curriculum designed to provide a seamless hands-on experience with SEL relays to protect motors, transmission lines, and transformers in a laboratory setting. Using SEL equipment trains students to program the relays to operate circuit breakers to clear faults, monitor system operation using a communication processor, and communicate with networked devices just as they would during their career as an engineer. Below can be seen a comparison of electromechanical relay and solid state relays.

	Solid State Rrelays	Electromechanical Relays
Electrical Noise	• Leverage zero voltage turn-on and zero current turn-offs • Generate minimal electrical disturbance	• Can generate significant signal noise as a result of mechanical system
Electromechanical - Power Consumption	• Feature low power consumption • Require little input power for switching loads • Ideal for creating more sustainable, energy-efficient solutions • High heat generation	• Power consumption is a function of the switching voltage and the internal resistance of the material being used in the switch • Require higher input power to operate
Electromechanical - Shock & Vibration	• Are highly resistant to shock and vibration • Are not susceptible to erratic or unreliable operation in demanding environments	• Mechanical system is subject to external forces that can lead to unreliable and erratic operation
Electromechanical - Switching Capabilities	• Respond to control signals in less than 100µs	• Can respond to control signals in 5 – 15 milliseconds (about 100 times slower than an SSR)
Compatibility with Control Systems	• Do not generate sparks or electric arcs and do not bounce electrically or mechanically • Have isolation levels up to 4kV • Magnetic fields have little effect on them • Are preferable to EMRs in environments where volatile combustibles are in use	• Arc when they interrupt current therefor not suitable for environments with volatile matter • Cannot operate in areas with large electromagnetic forces
Performance in Harsh Environments	• Do not generate sparks or electric arcs and do not bounce electrically or mechanically • Have isolation levels up to 4kV • Magnetic fields have little effect on them • Are preferable to EMRs in environments where volatile combustibles are in use	• Arc when they interrupt current therefor not suitable for environments with volatile matter • Cannot operate in areas with large electromagnetic forces
Positional Sensitivity	• Are positional insensitive • Are suitable for mounting in vertical or horizontal positions, "dead bug" position or adjacent mounting	• Mechanical system is subject to external forces • External forces must be perpendicular to relay action

Figure 3.1: *Comparison of solid state and electromechanical relays [4].*

3.2 Customer Archetype

Our customers will almost exclusively be universities and technical vocational colleges with the possibility for expansion into the secondary market of larger utilities. The technical universities and colleges would offer degrees or certificate training in the field of power systems, power protection, and microgrid systems (i.e. factory, ship, or power plant sized). Additionally universities with degrees in electrical engineering looking to expand their concentrations into the power sector are a prime target group for quick expansion. Our first customer is California

Polytechnic University, San Luis Obispo which is a university that offers power engineering degrees emphasis, but does not yet have a power systems protection laboratory in place.

We will focus on the individuals at universities that are in a position to be internal advocates for the purchasing of lab equipment and instruction material such as our microgrid lab. Such advocates are often the Dean of the College of Engineering and Department Chair of the Electrical Engineering Department. In order to sway these people to be interested and desire our product we will highlight factors that are dear to their respective positions that the lab would enhance. Such factors would include higher department and institution visibility on the national stage as having laboratory with technology that will aide in the future of utility grids on display. This will peak the interest from potential students and their parents leading to increased student recruitment. In addition to providing impetus to new students, the introduction of a utility industry specific laboratory could spur departments grants from nearby utilities and microgrid component sponsors such as SEL who hope to hire these students upon graduation and have a knowledge of the equipment. These internal advocates will immediately realize that as they expand their program offerings, industry sponsors and students will come flooding in. Additionally targeting schools with strong or developing IEEE Power and Energy Societies could help build internal advocacy by students to their department to purchase our microgrid system lab material and designs. Having these students on board for the project and its development at the particular university would in the end provided double value because not only would they have a modern lab course to offer but students could be involved in the building process as part of their senior projects just as is going on here.

The implementation of EPPL will quickly enhance the ability to establish a department's credibility in a short amount of time for new programs at a university. Because of the large size and complicated looking instruments it can be used as a main stopping point on department tours with industry and sponsors to highlight unique pieces that aide in the education process. The lab will be designed with this in mind to ensure it attracts both potential recruits and industry leading professionals. Beyond the aesthetics of new lab equipment and curriculum our customers will now have the ability to study/research physical power systems with a wide range of capabilities which is not common across the United States. Additionally once in place, departments will have the ability to expand upon the lab and use it for multiple classes with the help of their internal student projects. This will also attract employers and their pocketbook to assist in university events to higher their own recruitment on Power Engineering students with education in the latest technology.

It should be noted that there is already an existing market for training on the use of protective relays in grid conditions. There are currently two major companies manufacturing and providing services in the field of microgrid products and power system protection, Schweitzer Engineering Laboratories and General Electric. These companies design and manufacture relays as well as providing seminars and training sessions for customers and utilities. These trainings focus on how to properly program and integrate these relays into legacy and modern power systems equipment effectively. These programs from these companies are generally expensive and focus on a single relay at a time where the microgrid lab focus on single relays in each experiment and has the benefit of tying all these relays into the larger microgrid, giving students a basis for what to expect when working on larger utility power systems. Additionally it is good to be aware that under current industry practices SEL and GE will give these trainings and seminars but it is the utility or business's job to perform the actual installation of the equipment and there are few companies that provide outside installation and maintenance services to these entities.

Table 3.1: Solid State Relay Training Competitors

	Schweitzer Engineering Laboratories (founded in 1982) designs and manufactures power system protection equipment used by utilities, manufacturers, and sensitive oil/gas operations. SEL specializes in relays, circuit breakers, switches, and switchboards. A standard in protective relays. [5]
	General Electric (founded in 1892 by Thomas Edison) owns several large power industry subsidiaries involved with energy management, power protection and power/oil/gas production. Large industry footprint and vast history power engineering influence. [6]

The solutions by GE and SEL are similar in their material and technology but vastly different from the microgrid lab in their execution. Each company only does training on their own proprietary equipment as well as usually only providing education on one or two protective elements at a time. The microgrid laboratory overcomes these limitations by allowing for the use of both companies equipment as part of instruction. As part of the microgrid following the current industry standards, only SEL relays are being used as GE's market share has been steadily shrinking and SEL is dominating the market due to their higher reliability, customer satisfaction, and industry consensus.

3.3 Market Description

This project directly benefits students at California Polytechnic State University students in San Luis Obispo, providing them a lab environment to gain industry experience at the cost of state tuition. To reiterate the coursework validated and developed from this project will benefit specifically Cal Poly students emphasizing in utility power electronics and systems as well as other schools looking to implement power systems protection laboratory coursework to their catalog. The job market for students who have completed this course has but thus far untapped and jobs in protection engineering have classically been filled by engineers who've learned their skills in industry versus schooling. The companies looking to hire such protection engineers are all electric and gas utilities, refineries, large manufacturing plants, power plants, and commerce ports.

The current available power system protection courses are slim to none. There are exclusive courses being offered by protection device manufacturers at the expense of the individual or company. There are also very few options for online courses regarding power systems protection and how to program these devices. These are two major areas where the market is not well served. The investment needed to enter into this market would be the initial time and capital to purchase devices, setup a testing facility, and spending man-hours overcoming the learning curve per device. For instance each relay at a lab bench costs around $2,000-5,000 depending on the specific unit and with six relays per bench and six benches not including the periphery voltage meters and power supplies, the one time material cost of the bench equipment is likely to be near $100,000. Fortunately in setting up this current version of the lab, SEL has kindly donated much of the equipment needed for this lab course.

A major limitation to the completion of this project is the learning curve of the Schweitzer Engineering Laboratories (SEL) protective relays for new users. This project explores the use of five separate protective relays, each of which must be programmed specifically to protect a certain aspect of the overall microgrid. Consequently each relay has their own device settings. For us, the course developer, this learning curve is expected to take several months to overcome. A challenge upon completion of this project will be to provide the course taker knowledge of each relay in under 10 weeks.

Figure 3.2: SEL-587 Current Differential Relay[7]

A key area of strength we can leverage is the availability of resources and knowledge provided by SEL and Cal Poly. SEL has provided enough relays and protective devices to adequately furnish a laboratory of 20 students. Generally a course on utility protection devices from SEL University would cost upwards of $1,000 per day per device. This course provides Cal Poly electrical engineering students experience with industry standard SEL devices, making them ready and more desirable for employers in the power system and power electronics fields.

The department is also providing for the students currently working on the Microgrid project to have a formal training session with SEL on three relays that will occur in February as seen in the gantt chart in Chapter 4. This training will not only allow for the students to encounter less errors in their work on the relays, it will allow SEL to provide proper techniques that can be written into the lab manual for future students to learn before going into industry.

Key partners are SEL, Cal Poly Electrical Engineering professors, Cal Poly Electrical Engineering Department. SEL is a great asset in assisting the transfer of knowledge from industry professionals to students as well as the sole provider of protection devices for the laboratory. Cal Poly Electrical Engineering professors are the point of contact for any questions that may arise throughout the 10-week quarter for the coursework. Lastly, the Electrical Engineering Department is the key administrative figure in approving future coursework, resource budgeting, as well as deciding factor of any upgrades or revisions to the existing system.

Key potential customers that would be contacted are current students enrolled in EE406 and EE410, power systems analysis and power electronics respectively. The students in these courses are required to take two engineering technical elective laboratory classes in addition to two lectures to complete a graduation requirement. The coursework from this project would directly serve these customers as a major requirement and meaningful technical elective to add to the student's breath of knowledge.

3.4 Marketing Requirement

Based on the market study, students at Cal Poly lack a laboratory course in the field of power systems protection. The Microgrid Validation project meets this need by providing the Cal Poly student coursework that includes hands-on experience with industry standard protection devices, ultimately giving them a hiring advantage in the power systems field. Summarized in the table below is the unmet customer needs regarding this project.

Table 3.2: Customer Needs

Customer Needs	Importance of Customer Needs
Power Systems Protection Laboratory Coursework	• Must meet technical lab graduation requirement
Industry Experience	• Industry experience highly increases hiring advantage
Manageable Course Load	• Course spans 10+ weeks • Students have work loads from multiple other classes
Hands-On Experience	• Employers seek individuals with real experience with protective devices
Access to Industry Standard Devices	• Cost of devices is high • Device courses are expensive • Very few safe testing environments

3.5 Marketing Specifications

The Microgrid Validation Project gives the EE student concentrating in power systems protection, industry experience by offering hands-on experience with a lab scale grid. This project team is in the position to provide industry-ready students from Cal Poly by meeting the customer needs of a power systems protection laboratory course. Summarized in the table below are the marketing specifications that have derived from the customer unmet needs.

Table 3.3: Marketing Specifications

Customer Needs	Market Specification for Electric Power Protection Lab (EPPL)
Power Systems Protection Laboratory Coursework	● EPPL shall provide laboratory manual and verified/functional microgrid testing environment
Industry Experience	● EPPL shall prepare students for power systems protection jobs with use of industry standard protection devices (SEL)
Manageable Course Load	● EPPL shall cater the course load to the graduating electrical engineering senior ● EPPL shall encapsulate course load into 10-weeks of instruction
Hands-On Experience	● EPPL shall include physical use of SEL relays and access to physical microgrid

Access to Industry Standard Devices	• EPPL shall provide coursework utilizing Cal Poly EE Department resources of SEL donated protection devices

Figure 3.3: Marketing Datasheet

Project Name: Microgrid Validation

Unmet Customer Need: Lack of a power systems protection laboratory course and student experience with industry standard equipment at Cal Poly

Unique Value Proposition: The Microgrid Validation Project gives the EE student concentrating in power systems protection, industry experience by offering hands-on experience with a lab-scale grid.

Target Customer: Cal Poly EE students interested in concentrating in power systems

Positioning: The microgrid laboratory produces industry ready EE students from Cal Poly.

Pricing and Availability:
- Tuition
- S.P. Expo (product launch event)
- Spring 2018 (launch date)

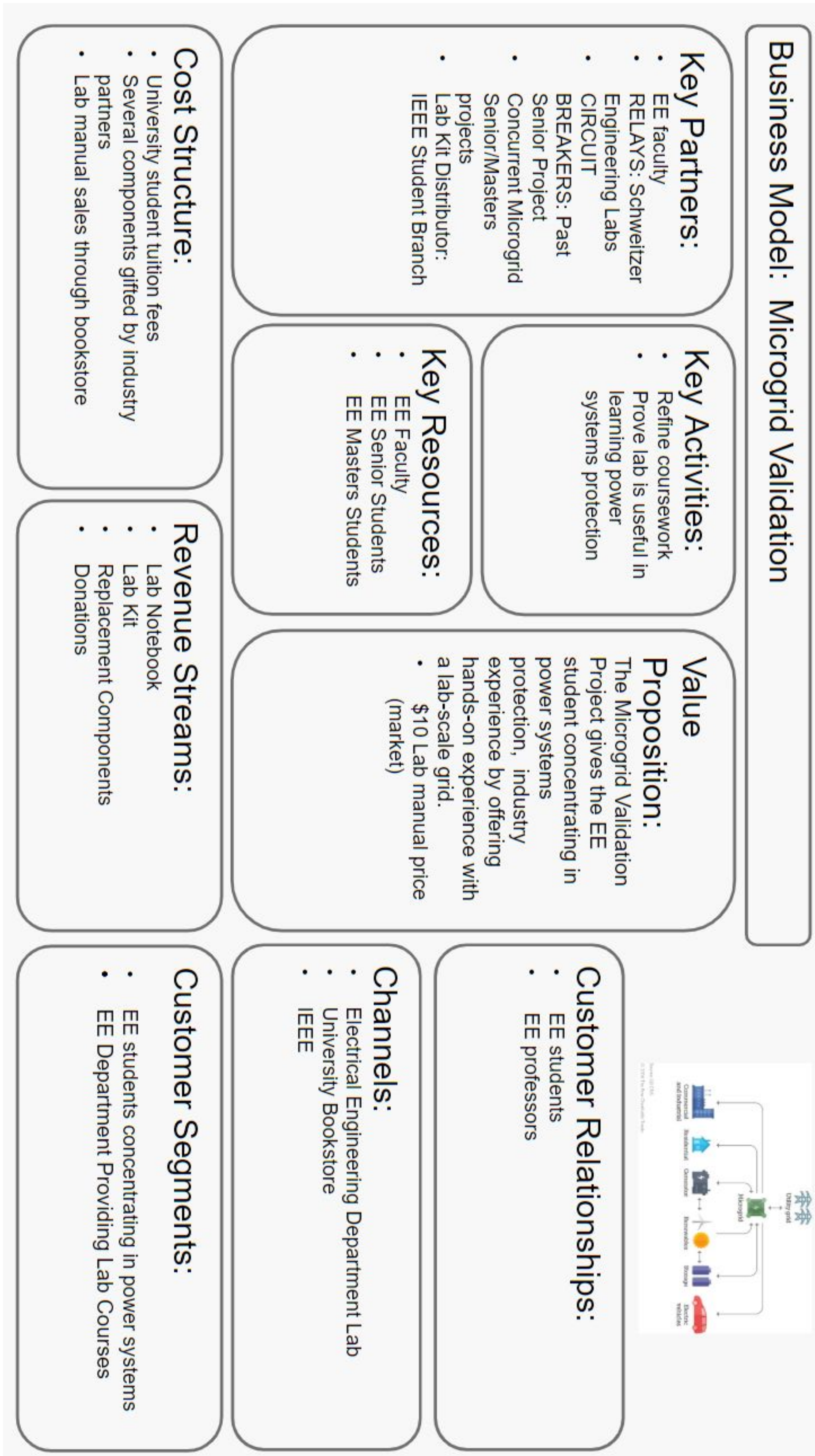
Product Objectives:
- Prepare students for industry
- Incentivizes industry to donate materials

Customer Benefits:
- Access to emerging technology and industry standard equipment
- Hands-on experience with lab scale power system

Sustainable Differentiation:
- Emerging technology system
- Industry equipment configured to emulate the larger grid
- EE Power Systems Brand

Disruptive Go-to-Market:
- Department newsletter promotion
- Weekly email promotion of new course offering
- Student word of mouth from those non seniors working on the project

Figure 3.4: Business Model Canvas



Chapter 4: Project Planning, Specifications, and Cost

4.1 Gantt Chart

Figures 4.1, 4.2, and 4.3 illustrates initial estimated timelines towards the completion of the microgrid protection lab. Figure 4.1 was a the estimated timetable for EE 460, which encompasses senior project research and planning. Figure 4.2 illustrates a proposed Gantt Chart for EE 461. The course covers design implementation and experimentation of proposed plans created in EE 460. The microgrid experiments are separated for all three team members Richard Terre, Vincent Tham, and Austin Kurth to work together and collaborate on. Each team member was given a specific protection relay for research and experimentation. The development of the lab experiments and evaluations divide into allotted times to ensure the completion of the project. Figure 4.3 details a proposed timetable for EE 462. EE 462 continues the work completed from EE 461 and ensures project completion by the end of the quarter. For EE 461 and EE 462, the Gantt chart contains color coded labels to indicate the student working on a specific experiment. Table 4.1 details the student and their assigned color.

Table 4.1: *Tasks Completed By Team Members*

Student Names	**Assigned Color**
Tasks worked on by Richard Terre	
Tasks worked on by Vincent Tham	
Tasks worked on by Austin Kurth	
Collaborated Tasks	

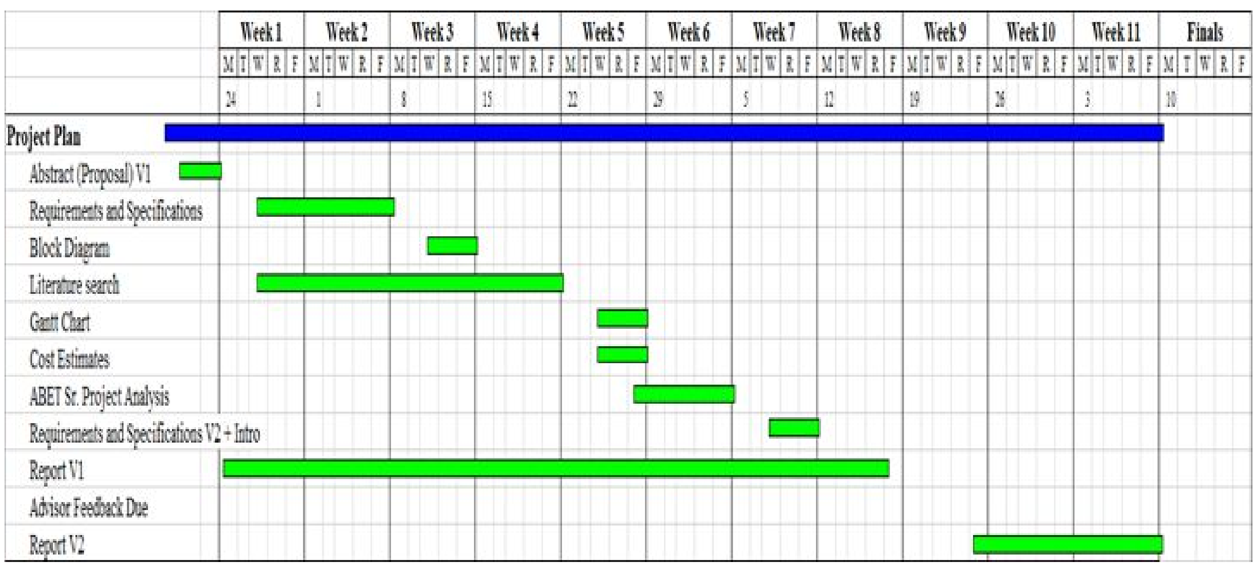


Figure 4.1: Initial EE 460 Gantt Chart

Figure 4.2: Initial EE 461 Gantt Chart

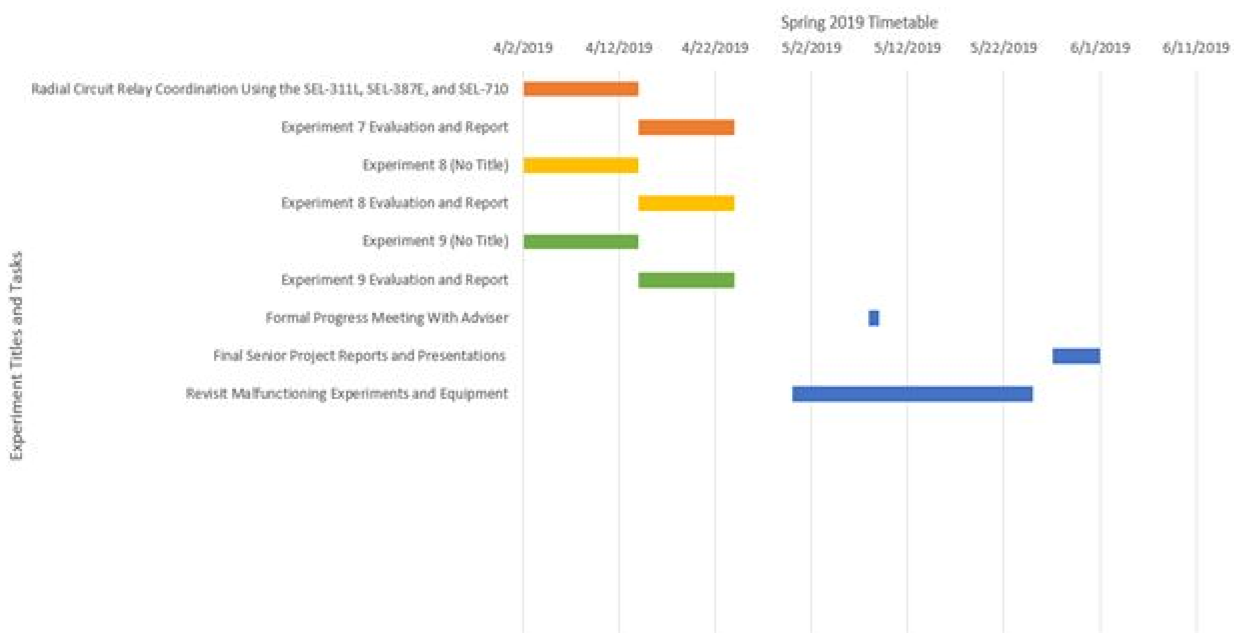


Figure 4.3: Initial EE 462 Gantt Chart

Updated Gantt Chart and Project Changes

After receiving relay training from SEL, we decided to include a digital portion of the protections lab alongside the physical experiments. The SEL-AMS software is very useful for relay testing because it does not involve large components for a power system and it is inexpensive for testing. Furthermore, relay testing with the AMS does not require 3-phase power. After learning about the useful capabilities, we transitioned from focusing on the physical experiments to developing the digital experiments for the SEL-311L, SEL-587, and SEL-387E. Figure 4.4 provides details for the progress made towards the AMS experiments throughout EE 461 and EE 462.

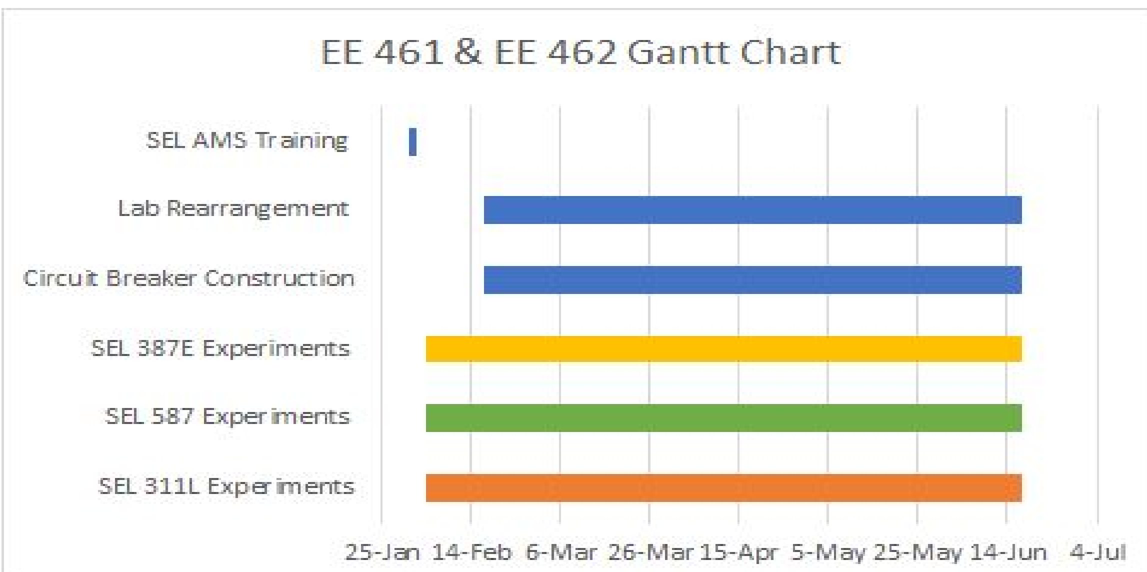


Figure 4.4: Updated EE 461 and EE 462 Gantt Chart

4.2 Requirements

The following table of engineering requirements was derived from the previously determined market requirements

Table 4.2. Engineering and Market Requirements

Market Specification for Microgrid Validation Project (EPPL)	Engineering Requirements
● EPPL shall provide laboratory manual and verified/functional microgrid testing environment	● EPPL shall consist of 9 experiments consisting of the use and operation of SEL relays
● EPPL shall prepare students for power systems protection jobs with use of industry standard protection devices (SEL)	● The Cal Poly microgrid shall utilize SEL relays for the protection of each power system device ● Use of SEL relays shall be in accordance with IEEE standards and common utility practice
● EPPL shall cater the course load to the graduating electrical engineering senior ● EPPL shall encapsulate course load into 10-weeks of instruction	● EPPL experiments shall be challenging but not time intensive and must be able to be completed within a standard 3 hour lab period ● EPPL lab manual experiments shall be able to be finished by the end of 10th week of instruction
● EPPL shall include physical use of SEL relays and access to physical microgrid	● The microgrid shall be built in a space suitable for physical testing and verification by students

• EPPL shall provide coursework utilizing Cal Poly EE Department resources of SEL donated protection devices	• The following SEL devices shall be used: ○ SEL-387E ○ SEL-311L ○ SEL-710 ○ SEL-587

4.3 Team Member Responsibilities:

As laid out in Chapter 5 on the Gantt chart team member responsibilities will be distributed for maximum time efficiency and to assure equal loading of the team. The responsibilities and projects have been assigned to each team member as such:

Table 4.3: Team Member Responsibilities

Austin Kurth	• Develop the systems and settings experiments for the SEL-587 • Construct Circuit Breakers • Rearrange lab room
Vincent Tham	• Develop the systems and settings experiments for the SEL-387E • Construct Circuit Breakers • Rearrange lab room
Richard Terre	• Develop the systems and settings experiments for the SEL-311L • Construct Circuit Breakers • Rearrange lab room

4.4 Testing and Verification

All devices received and utilized in this project will be acceptance tested by the manufacturer according to IEEE Acceptance Tests. The testing of the lab material for accuracy and feasibility will be done by Cal Poly Microgrid Team members as shown in Table 5. A request for approval will be sought from the electrical engineering department for the verification of lab material completeness. The end result will have the following components:

- Detailed reports of 8 Experiments
    - Each experiment will have up-to-date relay settings
    - Each experiment materials list will be updated
    - Each experiment will be verified to have been tested and approved by Cal Poly Electrical Engineering Department
- Compiled lab manual of 8 experiments for EE518 Power Systems Protection
- 6 constructed lab benches
    - Each lab bench will have the necessary equipment to conduct all 8 experiments

4.5 Bill of Materials

Table 4.4: Material Costs of the Power Protections Lab

Item	Number	Unit Cost	Total Cost
Banana Plug 5 Pack	30	$4.46	$133.80
Spade Wire Connector	3	$6.79	$20.37
12 AWG Ring Terminal (50 ct)	3	$7.90	$23.70
24V DC Power Supply	5	$15.96	$79.80
Motor Contactor	4	$37.14	$148.56
Auxiliary Contact Block	4	$13.74	$54.96
Velcro Strips	1	$12.25	$12.25
ABS Junction Box	4	$20.00	$80.00
Stripper/Cutter/Crimper	3	$13.99	$41.97
3-Phase Manual Switch	4	$52.00	$208.00
Black Banana Jack	24	$2.05	$49.20
Red Banana Jack	15	$2.05	$30.75

Green Banana Jack	5	$2.05	$10.25
Blue Banana Jack	20	$2.05	$41.00
Green Button	5	$11.15	$55.75
Red Button	5	$11.15	$55.75
Green LED	5	$8.85	$44.25
Red LED	5	$8.85	$44.25
Plastic Clips	20	$1.32	$26.40
Black 12 AWG Wire	1	$52.74	$59.97
Green 12 AWG Wire	1	$52.74	$59.97
Red 12 AWG Wire	1	$52.74	$59.97
White 12 AWG Wire	1	$52.74	$59.97
Blue 16 AWG Wire	1	$37.04	$37.04
SEL-311L	3	$5,000.00	$15,000.00
SEL-387E	4	$5,780.00	$23,120.00
SEL-587	4	$2,080.00	$8,320.00
SEL-710	1	$2,500.00	$2,500.00
SEL-AMS	9	$4,730.00	$42,570.00
SEL-Synchrowave Software	8	$500.00	$4,000.00
Yokogawa 2533 Digital Power Meter 3-Phase	1	$1,000.00	$1,000.00
Yokogawa 2533 Digital Power Meter 1-Phase	1	$800.00	$800.00
Yokogawa WT230 Digital Power Meter	1	$3,000.00	$3,000.00
		Total Cost	$101,747.93

Chapter 5: Lab Classroom Layout

The location for the protections laboratory is the former club room of the IEEE Power and Energy Society. Figure 5.1 illustrates a detailed schematic of the room arrangement. There will be two types of experiment setups present inside the lab, a physical experiment setup and a digital experiment setup. The physical experiments require 3-phase power to operate the system. The room is equipped with three lab benches all equipped with 3-phase power. The physical lab experiments consist of practical equipment utilized in industry. This ranges to power resistors, loads, 3-phase transformers, circuit breakers, and protective relays. There will be one specific relay at each bench: SEL-587E, SEL-387E, and SEL 311L. Initially, the plan was to allow the students to construct the circuits themselves for learning purposes, however due to the complexities of each system the experiments will be pre-built before each lab session. This ensures that students are given enough time to analyze the given system and to avoid time constraints.

The second experimental setup is the digital setup. The purpose for having a digital setup is for students to interact with protective relays without the requirement for 3-phase power. There will be 9 digital test setups. Each setup will involve a particular relay and a SEL relay test system. The SEL-RTS is designed for testing protective relays with low-level testing capabilities [8]. The relay test system comprises of the SEL-AMS and the SEL-5401 software. SEL-AMS and SEL-5401 are used in conjunction with one another. The SEL-5401 supports multistate testing for simulating power system changes and the SEL-AMS features analog outputs for inputs to the protective relays. The digital experiments allow for inexpensive testing of protection relays and low-risk of damage towards the relays.

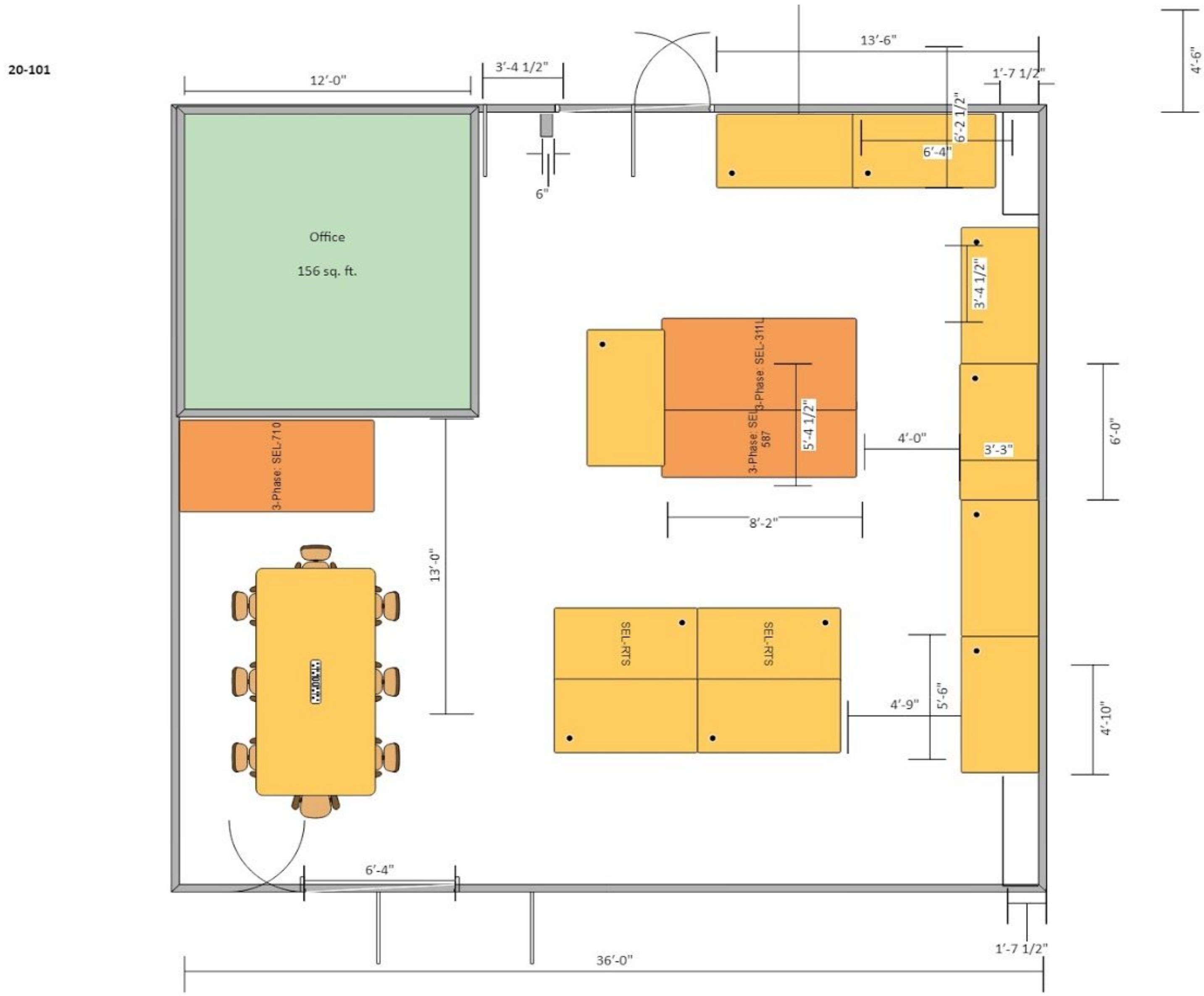


Figure 5.1: Schematic of Engineering East Room 101

Chapter 6: Circuit Breaker Development

6.1 Previous Work

The circuit breakers used in the Power Protections Lab are the third generation design of the breakers originally designed by Ozro Corelli [9]. The third generation breakers were developed by Yei Trinh and Garvin Yee under the direction of Dr. Taufik [10]. The lab requires a minimum of six circuit breakers for the three physical lab experiments. The allocation is broken down to three breakers for the 387E/587 bench, two for the 311L bench, and one for the 710 bench. Each of these breakers cost on average $220 in materials to build and they take several hours each in their drilling and construction.

The development of the circuit breakers finished in Spring 2018 where the senior project group built a single functioning breaker which they tested using a modified 710 relay experiment. The group had drilled holes into a second breaker box as well as gathered together three-quarters of the needed material to build it. We ordered the rest of the parts to finish the box and built it by following the wiring seen on the already constructed breaker. After testing this second breaker functioned as well as the first. The materials for two more breakers were ordered because of having access to a limited amount of funds at that point.

After drilling and constructing these two breakers we ran into a problem with the motor contactor specified in the Senior Project Report (parts number LP1K1201) and the one that was used on the breaker that was built by that group (parts number LP1K1210). This was a major problem because this caused us to order the wrong motor contactor for these breakers and it initially appeared that it would set back our project progress. The issue appeared minor because the change on the motor contactor was a normally closed (NC) that should have been normally open (NO). While we considered getting the correct part instead we found an unused NO switch on the auxiliary contact block. This switch was substituted and the breaker was finished. When the tests were conducted, the breaker worked perfectly as expected.

When more funding became available the final two breakers and their materials were ordered. These were constructed in the final week of the spring quarter.

6.2 Breaker Construction

The construction of these breakers is a mix of difficult work and time consuming labor to have a quality product at the end. In order to construct these breakers from start to finish a student must have the sufficient certification to use the drill press in the machine shops on campus (likely a yellow tag). The construction of the breakers is split into two parts. The first part is drilling the holes in the top of the breaker box and the second part is connecting all the buttons, lights, switches, banana terminals, and power to the drilled box and wiring the inside of the box.

To begin construction, take the uncut breaker boxes to one of the machine shops on campus during the week. Be sure to know which one is active that day as they trade off on days of operation. Sign in at the front desk and check out a standard drill bit set, push center punch, drill press, 29/32 drill bit, C clamp, and deburring tool. The holes in the front of the box as seen in Figure 6.1 below. It is important to use a drill press, not a regular drill as you will likely hurt yourself or damage the front of the box in the attempt. Make sure to also clamp the box down with the C-clamp when drilling the larger holes and the long hole on the right. The long hole on the right middle side of the box is the most difficult part to drill as you need to drill multiple holes right next to each other to create the long hole and each time moving the clamp to get the bit in the range where it is needed. Debur the edges of the holes and you are done. Time per box is estimated at 1.5 hours.

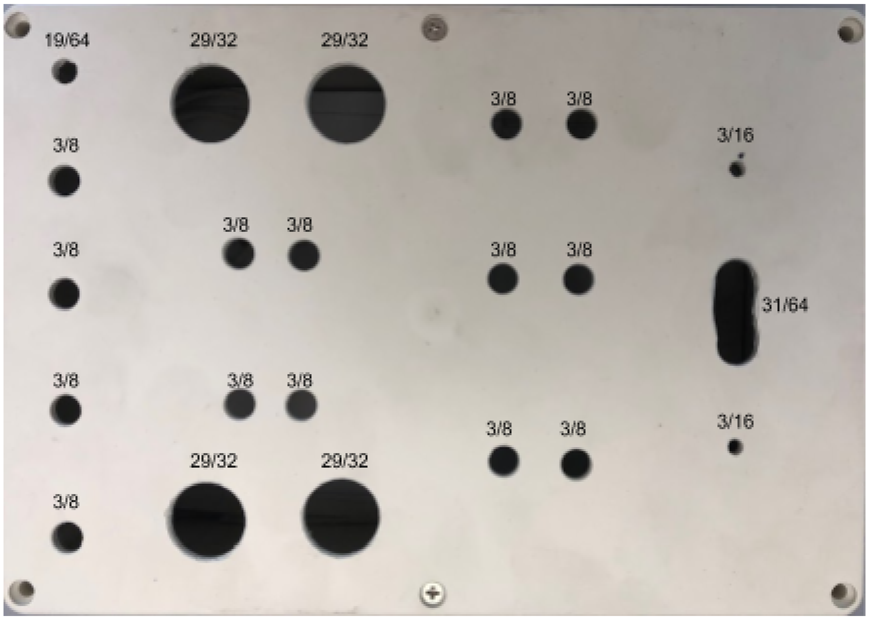


Figure 6.1: Drilled Circuit Breaker Box Unassembled

After the holes are drilled it is time to take the breakers back to the assembly room and start the wiring. Open the circuit breaker labeled as #1 (Figure 6.2) to use as a reference since this is one of the breakers that has the correct motor contactor. Build the new breakers in the same configuration as seen in breaker #1.

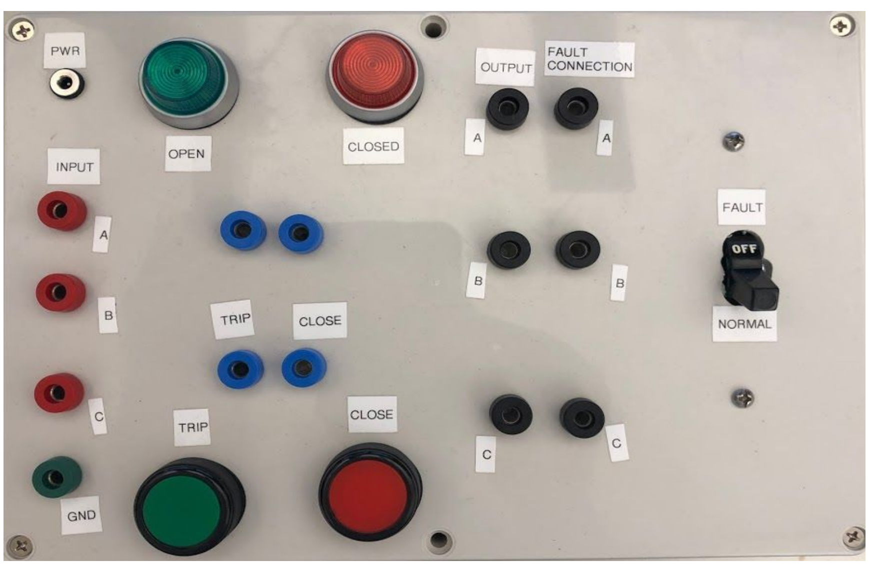


Figure 6.2: Assembled Circuit Breaker Box

Chapter 7: Experiments

7.1 SEL-311L Background

SEL 311L is a line current differential relay developed by Schweitzer Engineering Laboratories. Although the relay has the capability to perform differential protection similar to ANSI standard 87 protective relays, its primary use for the experiments is for overcurrent protection. Overcurrent relays monitor the magnitudes of currents flowing through a transmission line. The relay trips when the measured current exceeds the pickup rating of the relay. There are two separate overcurrent relay word bits, 50 and 51. 50 represents an instantaneous overcurrent element which trips immediately after a fault is detected. 51 represents an inverse-time overcurrent and it trips after a specified time delay. The delay time depends on the amount of fault current detected by the relay. High fault currents require short delays, whereas low fault currents require higher delays. Times when the relay can operate depends on several inverse-time overcurrent curves. These curves are U.S. standard and can vary from moderately inverse, inverse, and extremely inverse. The curves graphically illustrate the relationship between fault current magnitude and delay time before a trip [11].

Inverse-time overcurrent elements play an essential role in relay coordination across a power system. A time-dial setting for an inverse-time overcurrent relay defines a family of curves with similar slopes but different time delays [11]. A small time-dial setting (i.e. 0.50) corresponds to a short delay between when the relay detects a fault and when the relay trips. Conversely, a higher time-dial settings relates to longer delays. Figure 7.1 illustrates an example of an inverse time-overcurrent curves utilized to determine time dial and current tap settings of the relay. Working with the 50/51 overcurrent elements along with inverse time curves were integral when developing the AMS experiments. The physical experiment data and the pre-programmed relay settings from Kenan Pretzer's experiments served as the backbone for the digital experiments.

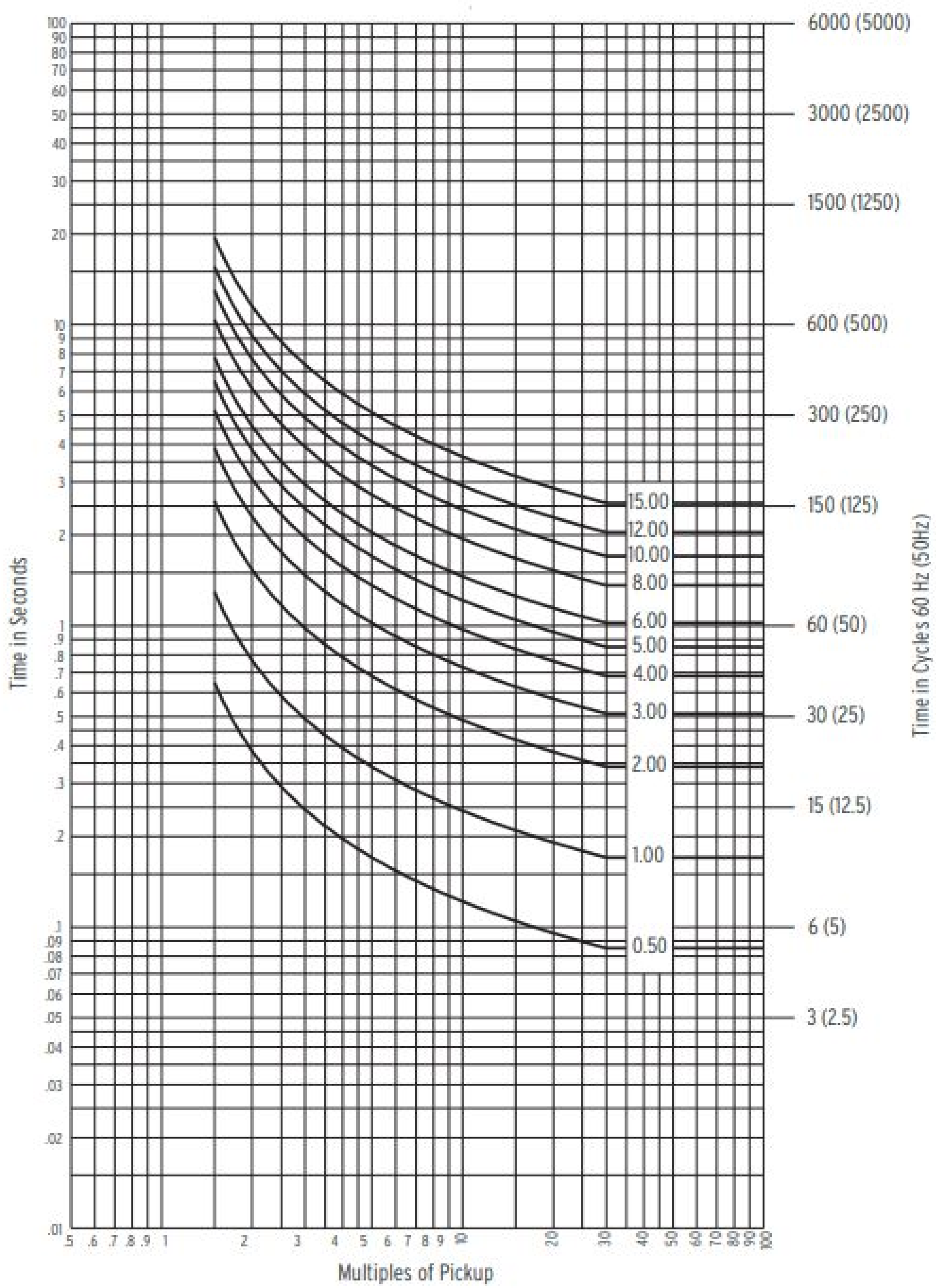


Figure 7.1: Moderately Inverse Time-Overcurrent Curves [12]

7.1.a Settings Test

The first overcurrent AMS experiment involves a simple settings check of the relay. The purpose for the settings test is for users to become familiar with the relay, the AMS, and the accompanying software. Figure 7.2 shows an example of what the AMS testing system looks like when connected to the SEL-311L relay. The AMS connects to the relay via C724 ribbon cable and an SEL-C234A Serial Cable. A serial cable can also connect a relay to a computer setup for relay testing and programming relay settings.

Figure 7.2: SEL-AMS Device Connected to the SEL-311L

The relay settings are premade following Kenan's settings for the physical system. However, the trip values were altered to slightly higher values for better observations of when the relay will trip. For example, a pickup current of 0.5A may be ideal for real power systems, but for testing purposes higher pickup currents need to be tested in order for the relays to not trip immediately. The settings test requires the user to create a 3-phase, line-to-line, and single-line-to-ground fault until the relay word bits 51GT, 51QT, and 51GT are asserted.

7.1.b Systems Test

The systems test requires that the students solve a given single-line-diagram and solve for any fault currents asked in the problem statement. Figure 7.3 illustrates the single-line diagram of the power system. The problem states to obtain the phase currents seen at fault location F for single-line-to-ground, line-to-line, double-line-to-ground, and 3-phase faults. The model mimics the physical system setup created by Kenan Pretzer. After the students solved for the necessary fault currents, they are instructed to set their own relay settings based on their calculations. This experiment is a good exercise to test students on their ability to solve for several fault conditions and translate those values to reasonable pickup and time dial settings for the relay.

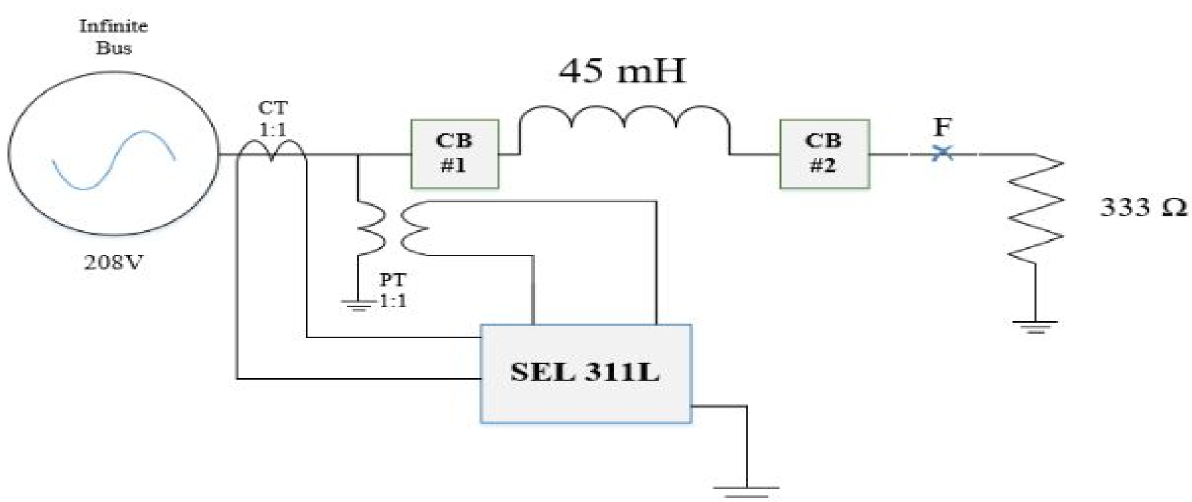


Figure 7.3: Single-Line Diagram for SEL 311L Systems Test Experiment

7.2 SEL-387E Background

The 587 and 387E relays have many similar functions such as overcurrent and differential, implied by the ANSI code of 87. The 387E has increased functionality with the added benefits of voltage protection and frequency protection. For a majority of this project the 587 was used for “Systems Tests,” where the relay is injected with values calculated from the physical system. In contrast, the focus of the 387E experiments was to focus on “Settings Threshold Tests,” to ensure proper operation of the relay. For both tests the same two protection schemes were investigated: overcurrent and differential. The details of how each scheme was tested is found in the lab manual created for EE518. The theory behind the “Settings Experiments,” is mentioned below and included in the background of each experiment.

7.2.a Overcurrent Settings Threshold Theory

Overcurrent (OC) protection is exactly as the name implies. The purpose of this method of protection is to observe currents within a zone of protection and only operating (tripping) when the current exceeds a certain threshold. Today there are three main types of OC protection: instantaneous, definite-time, and inverse time. When electromechanical relays were still used these three methods required three separate relays.

Instantaneous relays are used when relay coordination is not needed. Usually this is the least sensitive relay (highest pickup) as to not trip from inrush currents. Definite-time relays are used for relay coordination, having a time delay before operating thus allowing devices downstream the opportunity to operate first if an OC event occurs. Inverse-time relays are generally the most sensitive (lowest pickup). The speed of the relay tripping is determined by the magnitude of the current in other words their curved time current characteristic allows the relay to be slow to trip at low currents and faster to trip at high currents.

Modern microprocessor-based relays combine all three types of these relays into one OC device with settings for instantaneous, definite-time, and inverse-time to create a time current characteristic curve as seen in Figure 1. In summary, instantaneous settings consist of a current pickup that is constant, definite-time settings consist of a similar constant pickup but with a time delay aspect, and inverse-time settings consist of a curved characteristic.

The equation that describes the curved characteristic of an inverse-time setting is called the trip equation. These equations can be found in the SEL manuals of OC relays and are used to determine how long the relay will take to trip depending on the magnitude of the observed current. For example the U1 curve trip equation is:

$$tp = TD \times [0.0226 + \frac{0.0104}{M^{0.02}-1}]$$

Note: In this equation, t_p represents the relay operate time, *TD* represents the relay time-dial setting, and *M* represents the multiples of pickup current detected by the relay.

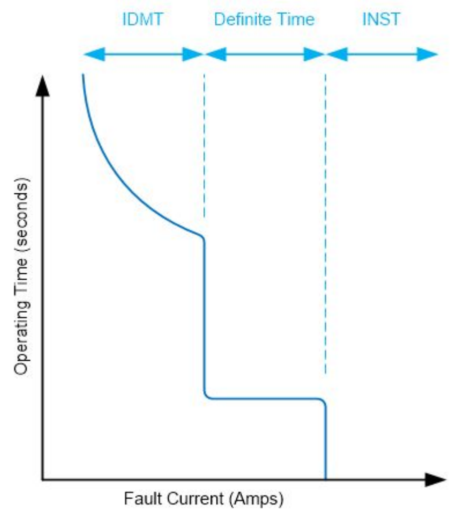


Figure 7.4: Combined Time Current Characteristics Curve

It is worthy to note that the previous description of overcurrent was describing in general that the relay will trip if the *current* is *over* a certain limit (pickup). However in practice, SEL has different options for what type of current you want to observe: phase, negative-sequence, or residual currents.

Phase OC elements operate based on a direct comparison between the phase current applied on the CT windings and the phase OC pickup. Negative sequence OC elements operate based on the comparison between the sum of negative sequence current vectors and the negative-sequence pickup value. Under normal operation, negative sequence current vectors are balanced and have 120 degrees differences, thus by summing the negative-sequence currents the vectors cancel and their sum is 0. Residual OC elements operate similarly but take the sum of the phase currents instead of the sum of just the negative-sequence components. Likewise, the sum of phase currents is 0 under balanced conditions.

As a protection engineer you can use one or all three of these *current* options to observe when designing a protection scheme. You can also use the different time curves to meet the desired design specifications. All of the overcurrent element options combine to form layers or levels of protection for a power system.

This experiment will specifically test the magnitude threshold of inverse-time phase OC pick up values. Secondly, it will compare the theoretical operating time as calculated in the prelab trip equations to the actual relay operation time. Thirdly, to test neg-seq OC elements. If time allows attempt to choose your own settings to test.

7.2.b Differential Settings Threshold Theory

There are three main categories of differential protection: differentially connected overcurrent, impedance stabilized differential, and percentage restrained differential. Each scheme differs in how it accounts for false differential currents. This experiment focuses on percentage restrained differential, meaning the relay operation (tripping) is based off the proportion between operating current and restraint current.

Operating current, IOP, is the difference between the winding 1 current entering and the winding 2 current exiting a protection zone. The restraint current, IRT, is the average of the winding currents.

$$Operating\ Current : I_{OP} = |I_{W1} - I_{W2}|$$

$$Restraint\ Current : I_{RT} = \frac{|I_{W1} + I_{W2}|}{2}$$

In terms of protecting a power transformer, like the physical 387E lab, percentage differential protection provides higher sensitivity at lower currents and lower sensitivity at higher currents. Thus the nature of the sloped differential characteristic seen in Figure 1 accounts for the fact that current transformers are more prone to saturation at higher levels of current.

The differential characteristic as set in a SEL relay is a constant minimum pickup, 087P, and two slope regions, SLP1 and SLP2, to achieve a percentage restraint that avoids false differential current at higher current levels.

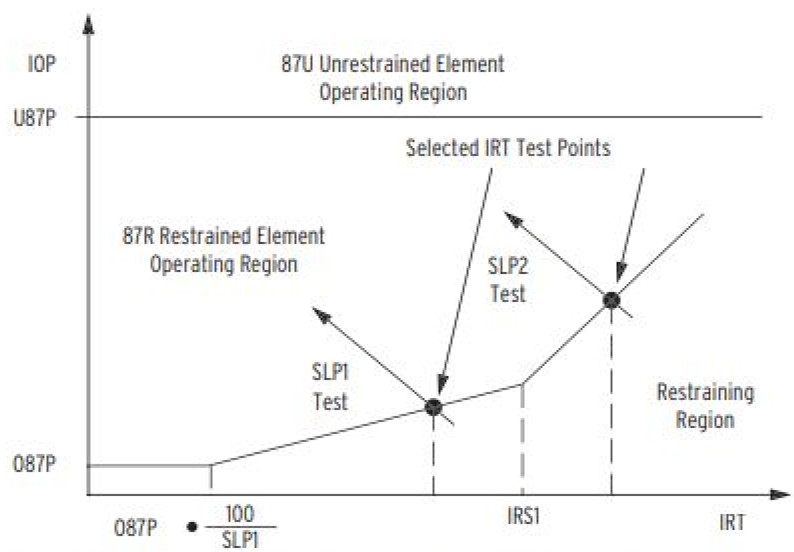


Figure 7.5: Percentage Restraint Differential Characteristics

7.3 SEL-587 Background

The SEL-587 is very similar to the SEL-387E, but with fewer capabilities. The SEL-587 supports differential and overcurrent protection of a two-winding power transformer. The only inputs to the relay are for the currents in winding one and winding two of the transformer and as such the SEL-587 does not measure voltage like the SEL-387E has the capability of doing. The SEL-587 protects the wye-delta transformer in the systems labs and a delta-delta transformer in the physical lab experiments. The relay has a fixed event recording period of 15 cycles (with only 3 cycles of prefault data). This limits the amount of information that this device can store compared to the other SEL relays utilized in this project. [13] The logic in the SEL-587 is identical to that of the SEL-387E described in the previous section.

7.3.a Systems Lab Experiments

While either the SEL-587 or SEL-387E could perform the system experiments because of their interchangeability for overcurrent and differential protection, the SEL-587 was selected for use in the system lab experiments. This is because of the simplicity of the relay allows for a more direct analysis of the calculations and theory behind the protection to facilitate student learning. The system labs use circuits identical to the ones used in the physical lab except that the primary side of the transformer is wye grounded instead of delta grounded. The key to note is that in these systems labs, as well as all labs created in this project, they use the AMS to provide operation and fault currents to the relay instead of a physical power system. Students do the calculations for the operating and fault currents of the system as part of the prelab and will use these values when they create the three state AMS tests. The AMS tests are split up to three states in order to represent the Pre-Fault, Fault, and Per-Fault states. The pre-fault state is meant to represent the steady state normal operating currents of the system. The fault state is used to input the magnitudes and phases of the fault currents calculated in the pre-lab. When this state is executed it is expected that the relay is able to identify the type of fault that happened due to these fault currents and trip the breakers. The fault state ends when the relay sends the trip breaker signal to the AMS which is programmed to skip to the final state when it receives this signal. The final state in the test is the post-fault state that begins once the AMS receives the tripped signal from the relay. This state has both windings at zero current because in reality the breakers on either side of the transformer would have tripped and therefore there is no current for the relay to measure.

Chapter 8: SEL Adaptive Multichannel Source (AMS)

8.1 Background

The SEL Relay Test System is designed to test protective relays without the necessity of setting up a physical system for the relay. The SEL-AMS functions as a digital power supply a user can operate in order to simulate various fault conditions based on a relay's pickup settings. The SEL-5401 test software is utilized in conjunction with the SEL-AMS. The program allows users to inject either single-phase or 3-phase voltage and current to the AMS, and as a result those values are read by the relay under test. Based on the contemporary settings of the relays and the values of the user-defined voltages and currents, users can test single-line-to-ground, line-to-line, and double-line-to-ground faults without the need for infinite buses, transmission lines, or loads.

Chapter 9: Project Review and Future Goals

9.1 Difficulties

1. Parts Ordering/Funding

The first drawback to any project is the funding. The funding for this project was no different. Between 3 group members we each had $200 from the EE department allocated for this project. However, the cost of each circuit breaker was close to $300 and the original plan was to order enough parts to build 12. With the help of our advisor, Dr. Majid Poshtan we leveraged the fact that this would be a teachable course to charge much of the cost to the electrical engineering department.

Once the hurdle of funding was acquired, there is a "sea of red tape," to navigate through whenever a purchase order goes out from the university. Although most parts were ordered in the earlier weeks of winter quarter, many parts have yet to arrive at the end of spring quarter. It would be advisable to order any time-sensitive components with the personal allowance and get reimbursed in the future to receive parts as soon as possible.

2. Transferring from physical to AMS setup

There was a level of understanding obtained regarding the operation of the relays when starting from Kenan Pretzer's physical lab setups. However the substitution of physical power system components with an adaptive multichannel source (AMS) was an entirely new concept to the team. The first step was to figure out how to physically connect the relay to the AMS through the appropriate SEL ribbon cable. Secondly on the software side, to use AcSELerator to communicate to the relay and SEL-5401 to communicate to the AMS. These steps were mainly learned at the SEL training workshop held in early February and would have been near impossible to learn without industry help. The physical connection between the relay and the AMS requires the user to dismantle the front plate of the relay to access the PCB.

3. Circuit Breaker issues

The main issue with the use of circuit breakers (CB) is misunderstanding the circuit diagram and function of each part of the circuit breaker. For one the name of the circuit breaker is misleading. The box contains a two-part function of being able to open or close a circuit (circuit breaker function) but also allows a student to generate faults (fault function).

For the CB function there is a manual open and close button that manually operates an electromechanical relay to open or close a 3-phase circuit. However, due to the design of the circuit, the manual open and close buttons do not function properly unless the blue trip terminals of the CB are shorted. This information was found in the documentation from the third iteration of the CB design but not easily understood otherwise.

4. Students need a certification to use the mechanical engineering shops on campus to build the circuit breakers

The circuit breaker faceplates required drilling and the nearest available drill presses were in the Cal Poly Machine Shops. Access to the machine shops requires a student to obtain a red tag certification qualifying the student through a physical and written test.

5. Learning curve

9.2 Future Work and Continuation Projects

Over the course of this senior project the vast potential of this lab and the specialized equipment students would have access to soon became clear. As much as possible these ideas and equipment were included in the experiments and systems in the lab room. However due to time and energy constraints there was no way to include all these things into the lab at this point in time. Instead it is hoped that future student senior project and master thesis built off the foundations that have been set by this lab. Below is a list of ideas for continuation as well as branch projects that one day could be included as experiments or as part of experiments in the Power Systems Protection Lab course.

1. In protection schemes relays often have the ability to trip different layers of circuit breakers in the case that there is a breaker failure in the first layer. This project would be focused on having the relays in the experiments trip the breakers but then receive a signal that the first set of breakers did not trip and so the relay would trip the second set of breakers. This project would end with this feature being able to be implemented with the physical breakers as well as on the AMS using the input/outputs on the back of the AMS

then included in the EE-518 lab manual on each lab experiment where applicable (1-2 students max)

2. As of now there are only three relays (311L, 387E, and 587) being used in conjunction with the AMS to create simulated fault conditions for overcurrent and differential protection. However there are many more relays available that are capable of being interfaced with the AMS and tested. According to the AMS software SEL-5401, the relays that are capable of being tested (and that Cal Poly has) are the 167, 167D, 221F, 221H, 300G, 351, 351S, 421, 587Z, and 710 (To know if the AMS will work with a relay open SEL-5401, create a new test and scroll down on the list of relay) (as of yet it is not known how to connect the 710 to the AMS). (Recommended 1 student per relay and 2-3 such students working together in a senior project)

3. Do relay coordination with the AMS using two 311L relays. This will probably use either the SEL-2032 (section 19.2 of Kenan Pretzers thesis) or SEL-2020 Communications Processor to connect two relays to the computer. These relays will need to communicate to each other as well as be connected to the same AMS. This setup can be seen on page 3-3 of the SEL-RTS manual available in room 101 (Recommended 2 students).

Chapter 10: ABET - Senior Project Analysis

10.1 Summary of Functional Requirements

Cal Poly's power system protection lab focuses on developing a laboratory course that enhances the learning experience of power systems protection. The project continues upon Cal Poly's existing microgrid project for the electrical engineering department. The laboratory course dedicates teaching EE students the fundamentals of relay-based protection systems and its practicality in real-world power systems.

10.2 Primary Constraints

Designing a new laboratory course for Cal Poly's EE curriculum requires many hours of planning and preparation. The key limiting factor for the project is the comfortability of operating the protection relay systems manufactured by Schweitzer Engineering Laboratories. Without the proper knowledge on how to operate the relay systems properly, laboratory experiment testing would extend for a longer period than anticipated. Chapter 2: Customer Needs, Requirements and Specifications, and Cost Estimates beginning on page 2 gives additional details about the primary constraints for the microgrid laboratory. Chapter 2 describes the marketing requirements and engineering specifications necessary for project completion.

10.3 Economic

SEL generously donated to the Electrical Engineering department all the protection relays used in the lab experiments, which correlates to few expenses spent for the project. The retail price for each protection relay ranges between $2000 - $5000. Purchasing the relay systems would cause additional expenses for the project. In addition, purchasing the relays would hinder purchasing other supplemental equipment. Labor costs factor in to the overall project development. Assuming labor costs range around 30 dollars per hour with 500 hours dedicated towards designing and developing the lab course, it costs roughly $100,000. The required equipment for purchase includes the circuit breakers and wires connecting the components together. Cal Poly's Electrical Engineering Department grants a fixed budget for students working on senior projects. The funds given towards the microgrid protection project focuses on receiving the correct equipment for the lab.

Gantt charts and cost estimates detail an estimated timetable for the completion of the protections lab, as well as estimated costs for the entire project.

10.4 If Manufactured on a Commercial Basis

Power system protection units exist to address specific energy resource needs. Depending on what type of protection schemes the customer desires, appropriate relay settings accommodate for that need. Given the educational value of the microgrid lab, the SEL protection relays plays a pertinent role to all lab experiments. Assuming the amount of labor cost is accurate, the total amount for installation costs around $100,000. The donated relay systems from SEL contribute to the completion of laboratory experiments on a regular basis.

10.5 Environmental

The microgrid protection lab does not harm the ecosystem or environment in any way possible. At SEL, security has always been an integral part of the company's foundation, and SEL as a long history of developing the most secure products and solutions [14] All the protection systems and equipment belong in a classroom setting and intended to isolate itself against external environmental factor.

Outside of a classroom setting, power systems protection aims to protect the environment by preserving power. Protecting a power system from hazardous fault serves as the first line of defense for people, property, and other areas susceptible to electrical fires. The microgrid lab not only teaches students how to operate protection systems, but also makes them aware of the implications it has with the environment.

10.6 Manufacturability

Schweitzer Engineering Laboratories (SEL) manufactures all the protection relay systems. The completion of the power systems protection lab depends on SEL to deliver all the equipment on time and to provide training for the students planning to operate the relays. The equipment should follow datasheet specifications provided by SEL's website and datasheets should allow for ease of operation and helpful background information.

10.7 Sustainability

The relay systems provided by SEL equips the EE department with a reliable monitoring system for detecting fault conditions within a power system. The protection relays given by SEL guarantee a 10-year warranty plan. Equipment replacement is only necessary if the relay systems break or malfunction. Recycling protection relays offers convenience even for new power system redesigns, Interconnects such as banana-to-spade wires, 12-16 gauge wires, and wire crimps replacement occurs when necessary, if they get damaged or worn out. Recycling protective relays whenever they reach the end of their lifespan reduces the negative environmental effects of utilizing electronic components.

10.8 Ethical

In the IEEE code of ethics it states that the safety and welfare of the public is paramount and as such engineering designs should not infringe on these either intentionally or unintentionally. Over the past couple of years and decades wildfires in California and other places in the world have been causing tens of billions of dollars in property/productivity damage and countless lives lost. Unfortunately many of the causes of these wildfires can be traced back to having been started from a utility power line which more often than not could have been prevented. This lab course presents the potential for students to learn how to effectively work with, design in, program, and operate protective elements and relays into a power system which can provide for a decrease in the likelihood that a fault will be sustained long enough to cause damage in their environments. It is therefore our ethical obligation to create this lab and offer it to students in the hope that lessons learned here can be implemented safely in utility operations and mistakes can be made in a safe environment and learned from such that they are not repeated again. We hope that this project will live up to these goals and provide for a safer and more reliable power grid through creating competent and capable protection engineers.

10.9 Health and Safety

Cal Poly’s microgrid team advises future students to enroll in the course on their own volition. The lab involves operating power systems in the high-voltage range (around 200V), therefore students should evaluate safety precautions before enrolling in the course. The microgrid protection team ensures the safety for both students, faculty, and equipment. Effective safety practices for the course include de-energizing live circuits whenever possible before servicing them and utilizing appropriate tools and personal equipment to mitigate hazards efficiently [14].

10.10 Social and Political

Students and faculty members encompass the primary stakeholders for this project. The success of the microgrid lab depends on a student's willingness to learn about power systems protection and the faculty's efforts to guide students towards completing all the experiment Other outside stakeholders include parents or guardians that overlook their child's education and assists in paying for course fees. SEL also benefits from the lab because their equipment keeps the lab course functioning. Students who enroll in the protections lab can mention they have experience operating power system protection relays manufactured by SEL. Recruiters from power systems companies also benefit from the microgrid lab. Recruiters in the power systems industry look for capable students who demonstrate adept abilities in operating power systems. Power systems protection is an important aspect in the power industry and mentioning the experience with power systems protection in lab fortifies understanding of the course material.

10.11 Development

Operation of the SEL relays poses as the main obstacle for this project. In addition, proper knowledge of transformer connections, circuit breaker operation, and relay coordination time indicates a successful lab. The power systems protection course intends to teach new students the fundamentals of power systems protection and encourage students to pursue more knowledge about protections engineering. The literature search conducted for this project provided useful information about SEL's protection relays and how protection systems impact the quality of power system production. Upon project completion, I anticipate a clearer understanding about the importance of protection relays and proficient knowledge on how to operate unique protection schemes.

Chapter 11: References

[1] Quara.com. (2018). *When a fault occurs on a line, what happens to the voltage and current?*. [online] Available at:
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Image used to illustrate fault on a line detectable and correctable by relay protection

[2] T. Luna, "California utility equipment sparked more than 2,000 fires in over three years", *latimes.com*, 2019. [Online]. Available:
https://www.latimes.com/politics/la-pol-ca-california-utilities-wildfires-regulators-20190128-story.html. [Accessed: 08- Jun- 2019].

Information on damage done by fires due to utility equipment.

[3] A. Shaban, *Power Systems Laboratory Manual.* Cal Poly San Luis Obispo, San Luis Obispo, CA. Revised Spring 2016.

This reference is relevant to the Microgrid Validation Project because it is the current coursework available to electrical engineering students that utilizes SEL relays. This laboratory manual will also be validated, revised, and improved to expand the use from a single relay to five different relays provided by SEL.

[4] arrow.com. (2018). *Solid State vs. Electromechanical Relays*. [online] Available at:
https://www.arrow.com/en/research-and-events/articles/crydom-solid-state-relays-vs-electromechanical-relays [Accessed 4 Dec. 2018].

Image used to illustrate the differences between solid state and electromechanical relays

[5] selinc.com. (2018). *Schweitzer Engineering Laboratories*. [online] Available at:
https://selinc.com/ [Accessed 22 Oct. 2018].

Information about SEL products and services. For the purposes of this project SEL is a competitor in the power protections equipment training market.

[6] Ge.com. (2018). GE | *Imagination at Work*. [online] Available at: https://www.ge.com/ [Accessed 22 Oct. 2018].

Information about GE products and services. For the purposes of this project GE is a competitor in the power protections equipment training market.

[7] selinc.com. (2018). *SEL-587*. [online] Available at: https://selinc.com/products/587/ [Accessed 4 Dec. 2018].

Image used to illustrate SEL relay and interface

[8] Cdn.selinc.com, 2019. [Online]. Available: https://cdn.selinc.com/assets/Literature/Product%20Literature/Data%20Sheets/RTS_DS_20080530.pdf?v=20150812-155323. [Accessed: 08- Jun- 2019].

Used to give more background on the RTS software and AMS system

[9] O. Corulli, "Motor protection Experiment using SEL-710", California Polytechnic State University, San Luis Obispo, 2013. Available at: https://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1236&context=eesp

Information on the senior project that first developed the line of circuit breakers further developed by Cal Poly students

[10] Y. Trinh, G. Yee, "Circuit Breaker Module", California Polytechnic State University, San Luis Obispo, 2013. Online, https://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1445&context=eesp

The senior project that developed the third generation circuit breakers used in the protection lab.

[11] K. Pretzer, *PROTECTIVE RELAYING STUDENT LABORATORY.* Cal Poly San Luis Obispo, San Luis Obispo, CA. 2017.

This reference is relevant to the Microgrid Validation Project because it is the reference that will be validated over the course of this project. Pretzer's reference provides coursework that was written a year ago that needs to be updated and revised.

[12] [5] Schweitzer Engineering Laboratories, Inc., "Line Current Differential Protection and Automation System," SEL-311L datasheet, 2001.

[13] K. Pretzer, *PROTECTIVE RELAYING STUDENT LABORATORY section 3.4.* Cal Poly San Luis Obispo, San Luis Obispo, CA. 2017.

[14] selinc.com. (2018). *Schweitzer Engineering Laboratories*. [online] Available at: https://selinc.com/ [Accessed 17 Nov. 2018].