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Senior Project Design: Circuit Breaker Module

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ABSTRACT

The circuit breaker module for this design project is a proof of concept that demonstrates the functionality, feasibility, and attainability of a consumer grade power systems analysis device suitable for college laboratory use. The goal of this project was to create the final iteration of a module that has been developed and refined over the course of previous years. The Cal Poly Electrical Engineering Department intends to use this design to produce circuit breaker modules intended for fault analysis. With the current changes made to the previous modules, the current circuit breaker is lighter, safer, and more universally reproducible. The use of a generic plastic enclosure ensures that others outside of Cal Poly may find the means to build this module themselves. The redesign of the faceplate was done to prevent module users from touching exposed live wires when trying to reach the mechanical switch. Finally, more affordable, adequate component alternatives were found so that Cal Poly will be able to reproduce this design for years to come.

ACKNOWLEDGEMENTS

Dedicated to our family, our friends, and our mentors.

Thank you all for your unwavering support and encouragement.

TABLE OF CONTENTS

CHAPTER 1.....	5
CHAPTER 2.....	8
CHAPTER 3.....	11
CHAPTER 4.....	14
CHAPTER 5.....	18
CHAPTER 6	32
REFERENCES.....	34
APPENDIX A: BILL OF MATERIALS.....	36
APPENDIX B: DETAILED PROCEDURE	37
APPENDIX C: ANALYSIS.....	49

LIST OF FIGURES

Figure 3.1	Level 0 Block Diagram.....	11
Figure 3.2	Level 1 Block Diagram	12
Figure 4.1	Enclosure for Circuit Breaker.....	14
Figure 4.2	A Top-Down Comparison for the Previous and Current Circuit Breaker.....	15
Figure 4.3	Rough makeshift stencil used to drill holes into the lid of the enclosure.....	16
Figure 4.4	Circuit Schematic using Circuit Elements.....	17
Figure 5.1	Circuit Breaker connected to the SEL-710 Relay.....	19
Figure 5.2	Circuit Breaker connected to the Induction Motor and Multimeter.....	20
Figure 5.3	Radial Resistive Circuit Single-Line Diagram.....	21
Figure 5.4	Line to Line Fault Analysis.....	28
Figure 5.5	Three Phase Fault Analysis.....	29
Figure 5.6	Undervoltage Trip Analysis.....	30
Figure B1	QuickSet Main Window.....	38
Figure B2	SEL-710 Communication Parameters Window.....	39
Figure B3	Identifying SEL-710 Relay Family, Model, and Version.....	40
Figure B4	Identifying SEL-710 Relay Part Number.....	40
Figure B5	Example SEL-710.....	40
Figure B6	Saving SEL-710 Settings.....	41
Figure B7	Choosing Location for New SEL-710 Relay Settings Database.....	41
Figure B8	SEL-710 Settings Editor Main Window.....	42
Figure B9	SEL-710 General Settings.....	42
Figure B10	SEL-710 Breaker Monitor Settings.....	42
Figure B11	SEL-710 Main Settings.....	43
Figure B12	SEL-710 Main Settings, cont.....	43

Figure B13	SEL-710 Phase Overcurrent Settings.....	44
Figure B14	SEL-710 Residual Overcurrent Settings.....	44
Figure B15	SEL-710 Negative-Sequence Overcurrent Settings.....	44
Figure B16	SEL-710 Undervoltage Elements.....	45
Figure B17	SEL-710 Trip and Close Logic.....	45
Figure B18	SEL-710 Logic 1, Slot A Output Logic.....	46
Figure B19	SEL-710 Port F Settings.....	47
Figure B20	SEL-710 Trigger Lists Settings.....	48
Figure B21	SEL-710 Event Report Settings.....	48
Figure B22	Send Modified Settings to the SEL-710.....	48

LIST OF TABLES

Table 5.1 Per-Phase Sequential Points of Connection.....23

CHAPTER 1 - INTRODUCTION

Electricity transmission dates to the 1880s when Thomas Edison installed six large power plants each with its own steam driven generators called dynamos for the Pearl Street station. The station was connected to customers through a network of underground wires running inside tubes [1]. With the plants and underground wires, Edison energized America's first power grid providing electricity to customers within a few city blocks with his DC (direct current) distribution system. However, in the 1800s, it was impossible to easily convert DC voltages to a higher one. This resulted in one major drawback of Edison's system which was its limitation to one-mile radius or less. The need to transmit electricity at higher voltages was important to minimizing power loss. Since this was impossible for Edison, this need paved the way for AC (alternating current) technology to arise [2]. At the front of this changing technology was Nikola Tesla who worked with entrepreneur George Westinghouse and other engineers to make long distance transmission possible. Using transformers, they were able to increase or decrease AC voltages which increased efficiency and reduce transmission losses as well as allowing Westinghouse's transmission lines to reach longer distances than Edison's lines. With Edison standing on the side of DC power and Tesla on the AC power side, the two were competing to see which power was superior. This competition is now known as the War of the Currents [3]. The height of the war took place at the Chicago World's Fair where General Electric and Westinghouse bid against each other to see who could electrify the fair. General Electric bid using Edison's direct current for \$554,000. Westinghouse ended up winning the bid since he could electrify the fair for \$399,000 using Tesla's alternating current. Subsequent similar events would follow the event that took place at the Chicago World's Fair showing the dominance AC

held over DC. In 1888, Oliver Shallenberger invented an AC watt-hour meter that gave Westinghouse the means of measuring Amperes per hour on an alternating current circuit. This invention did not consume any power, so customers were only being charged for the power they used [4]. It also allowed consumers to monitor their own consumption. It was clear that AC was the better system. However, development of DC systems continues to this day. In 1901, Peter Cooper Hewitt invented mercury-arc valve which, 30 years after it was invented, was used in many HVDC design and systems. In the 1970s, solid-state devices were becoming a standard in HVDC systems [5]. The early history of power systems is the foundation in which today's industry will continue to develop and improve upon. It is an important point of reference today and will still be in the future.

Modern power systems are expanding to this day, and a larger grid creates a bigger opportunity for problems to arise. These problems, or electrical faults, can be caused by a variety of things, ranging from weather conditions to equipment failures to human error [6]. The impact of a fault can be damaging to equipment, harmful to personnel, and can even cause fires. In order to mitigate the occurrence of electrical faults, electrical system protection devices are implemented in the use of power systems. These protection devices are utilized in the form of fuses, relays and circuit breakers. Focusing on the circuit breaker, Thomas Edison had described one in an early patent in 1879. However, it wasn't until 1924 when Hugo Stotz designed the first iteration of the modern circuit breaker [7]. Today, circuit breakers are still improving and evolving to keep up with modern power systems, to the point where companies are looking into 'smart' circuit breakers that can be remotely tripped [8]. This continuous development reinforces the importance of understanding circuit breakers and how they are used to combat electrical faults.

Future power engineers should be able to grasp the concepts of circuit theory and the functionality of system protection devices in order to be prepared for the potential issues that could arise on the job. However, in order to mimic a real-world system in a controlled environment, there needs to be equipment provided to these future engineers so that they have early exposure to this side of the industry. This equipment will be used to simulate a microgrid, a small scale modern power system, and will be in the form of power generated from the grid, solar panels, and protection equipment such as circuit breakers. The future power engineers will be able to learn all these fundamentals in the form of a college-level laboratory course while they are students. Universities should be able to adapt and implement such a course to help students understand what a modern power system such as microgrid system is, how it works, and what problems can arise. This hands-on, real-world replica of a power system that is constrained to a controlled setting would provide practical experience for a future power engineer to take on a job in the industry.

CHAPTER 2 - BACKGROUND

This project is a continuation of Ozro Corulli's 2013 senior project where he developed an additional lab experiment based on the SEL-710 motor protection relay for the Power Systems Laboratory course, EE444. The SEL-710 is a microprocessor-controlled relay capable of reading voltage and current levels. It can detect an anomaly which will trigger the relay to send a signal to a circuit breaker to open the circuit in order to protect it from overload current. Corulli designed a circuit breaker that interfaces with the laboratory setup to allow students to simulate the various kind of faults such as single-line-to-ground or line-to-line fault. The purpose of Corulli's senior project as well as Kenan Pretzer Master's thesis and Ian Hellman-Wylie's and Joey Navarro's senior project is to create a future microgrid protection lab course. In 2016, three electrical engineer students adopted Corulli's design and created a new model for the circuit breaker box for their senior project. Barley, Chung, and Scozzari attempted to build a second iteration of the circuit breaker box, improving on old characteristics like removing lab bench DC input voltage and implementing an AC to DC wall adapter to minimize the number of manual physical connections to operate the module.

The future microgrid protection lab will enhance the lectures covered in the power system course by giving students the opportunity to perform experiments based on power system lectures and theories. It will give students hands-on learning experience and help them visualize various faults using the circuit breaker. Industrial electric motors can cost millions of dollars so students coming into the field from school will have experience in basic power system protection.

This project is intended to improve and redesign the circuit breaker to be used in the future microgrid and power system protection labs. With that in mind, it is important to reference the previous iterations of this circuit breaker to find where corrections and improvement can be implemented. The main document referenced for this senior project is the report of the three students, Barley, Chung, and Scozzari, who created the second iteration of the circuit breaker box for their senior project. Their project references Corulli's senior project report, the prototype model for the circuit breaker. Each report has their own set of information, which has an extensive list of parts used, the process of designing the faceplate, the internal hardware configuration, and lastly the assembly process of all the pieces to the final product. The information provided has greatly helped accelerate the design process improvements. The primary planned improvement from the modified design is to relocate the switch used on the circuit breaker module. With the current design, the switches are dangerously close to the output. Since the output will get hot, the switch will be placed away from the output to ensure it is safer from harm which increases its lifetime.

With size being a strong hindering factor for the box design, the chassis will be redesigned as well. Instead of using a metal chassis with a face plate, a plastic enclosure will be implemented instead. It is a much safer material to use, and a much more affordable one. It will ensure that the box is not fully conductive, and it will more economical, as well as lighter to carry and move around. This improvement enables the box to have more room for connection placements, and to have more room for the switch relocation.

There was discussion for the DC power supply for the circuit breaker module to revert back to the 125 VDC input using the DC power in the current machines lab. The relative location of the switch and the power supply are both aspects seen in Corulli's design so his design will be

referred to more than the modified design. However, the present configuration using a commercially available AC to DC wall adapter is both safer and more convenient, as it is lower voltage and it allows the circuit breaker box to be used in places with a wall outlet as opposed to just a laboratory with 125 VDC. The issue is that the laboratory benches have a finite amount of wall adapters, and when the laboratory class uses this circuit breaker box with relays, there may not be enough room to properly conduct the experiment. Ultimately, the design concluded to keep the modified AD to DC wall adapter.

In order to ensure that the planned senior project is the final iteration of the circuit breaker box to be implemented in the labs for student use, the Cal Poly Electrical Engineering Department will have a strong influence on the project. Dr. Ali Shaban, Dr. Taufik, and graduate student Eric Osbourne have been referenced to make sure all the improvements are in line with what the Electrical Engineering Department feels are necessary to implement the circuit breaker boxes in the laboratories for student use.

CHAPTER 3 - DESIGN REQUIREMENTS

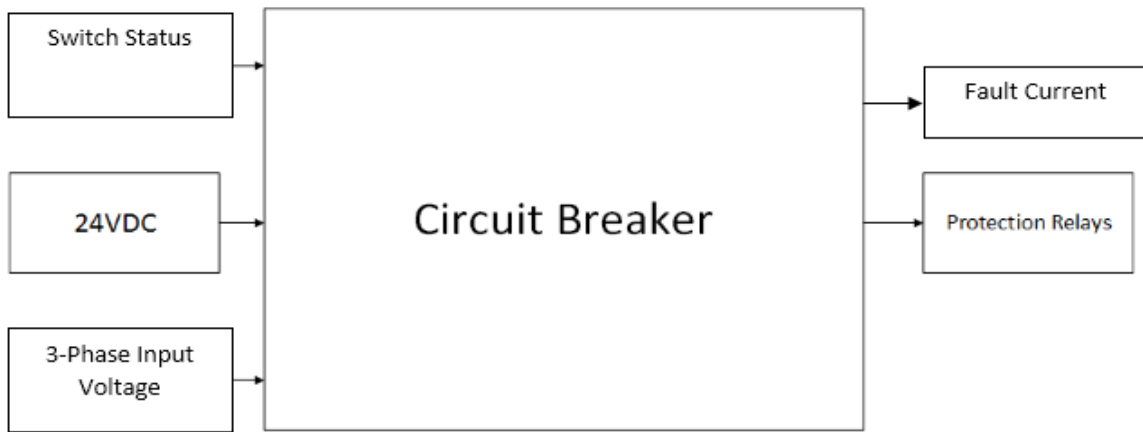


Figure 3.1: Level 0 Block Diagram

Figure 3.1 depicts a level 0 block diagram for the circuit breaker, showing its inputs and outputs. In the level 1 block diagram, the basic internal structure is added, as seen in Figure 3.2. The block diagram has been taken directly from the previous report. The circuit breaker receives its DC power from the AC Adapter which connects to the LEDs, Manual Close/Trip Buttons, and Motor Contactor. The LEDs indicate whether the circuit breaker is open (Green) or closed (Red). The open or closed state can be controlled through the manual close/trip buttons. The motor contactor, LP1K1210BD, and auxiliary contactor, LA1KN22M, contains series of switches needed for proper operations. The mechanical switch connects the circuit breaker's output to the 3-phase fault so it can be switched ON to directly connect the output to fault or OFF to disconnect the fault from output. The protection relay monitors the whole operation and will trip the circuit breaker if it is not operating normally.

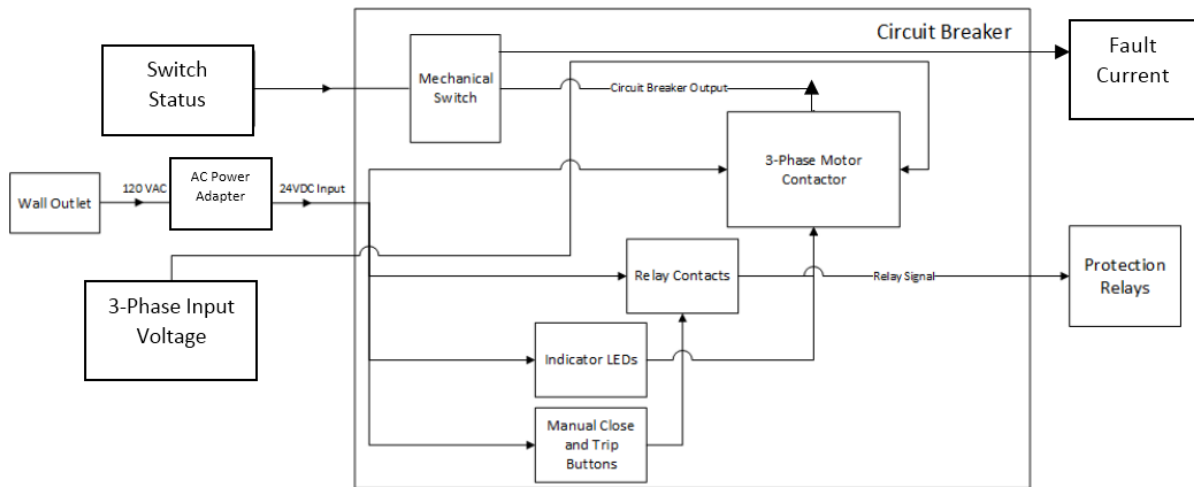


Figure 3.2: Level 1 Block Diagram [9]

This project's primary goal is to address the issues of its predecessors. The main improvement is to relocate the switch from its position in the middle of all the spade connections to some place where it will not be close to exposed metal. The project will also remove three banana plugs from the front panel to clear up room. The circuit breaker will also have a larger chassis than the previous model, in order to have more space for component placement. The chassis will also no longer be fully metal, and will be made of plastic instead.

The original Circuit Breaker was a metal chassis that was very confining. Its dimensions were too small for optimal component placement. Due to this restriction, the switch used to control the faults was placed between six spade connections. This suboptimal placement is extremely hazardous, as one could get shocked by touching exposed connections while conducting experiments with the circuit breaker. With safety being the primary concern, moving the switch is the most important improvement.

In order to further improve upon the Circuit Breaker, the chassis will now be a plastic stock enclosure. This change is an economic change, because it is cheaper to buy a plastic enclosure than it is to buy premade metal chassis. This improvement is also an efficient change, because the dimensions of the new enclosure are larger, it allows for more freedom in component placement. With size being one of the primary constraints, it will be taken care of in this final iteration of the Circuit Breaker. Plastic is also a much lighter material than metal, so it will be lighter to carry around.

CHAPTER 4 - DESIGN

The new circuit breaker was designed by analyzing the previous designs. A decision was made to stick to the design closest to the most recent design due to it requiring a much lower voltage meaning cheaper parts compared to a higher voltage supply. The bill of materials of the recent design was reviewed to ensure the availability of parts. To improve the previous design, some parts were rearranged to fit on the new front plate. The new plate was longer than the previous which led to more spacing between each part horizontally. This allowed the manual switch to be placed in a safe location away from the banana connections that have high voltage across them. The location of the switch is important since users of the circuit breaker box will interact with that part the most so putting the switch far away from the banana connections greatly lower the chances of potential accidents.



Figure 4.1: Enclosure for Circuit Breaker [10]

In order to make sure this circuit breaker can be replicated outside of the Cal Poly lab, a stock universal electric project enclosure was found to be used as a chassis for the experiment. The dimensions of the new enclosure are 10.4 in x 7.2 in x 3.2 in. This is slightly larger than the older models, and is much lighter. This will allow for easier transportation and optimal component placement.



Figure 4.2: A Top-Down Comparison for the Previous and Current Circuit breaker

As shown above, the new design places the switch far from the output banana jacks, which is a huge improvement to safety. The size is not much larger, but it is more than enough to allow for optimal component placement. The previous design used a 24 VDC laptop charger which connected to a DC jack that was held in place with hot glue, floss and cardboard. In order to properly mount the DC jack, a new jack was chosen. A new cheaper laptop charger was also found which reduces the cost of the circuit breaker. The new circuit breaker improves the previous design by addressing issues with the layout and cost. The new layout improves a safety issue present in the previous design and cost was overall reduced.

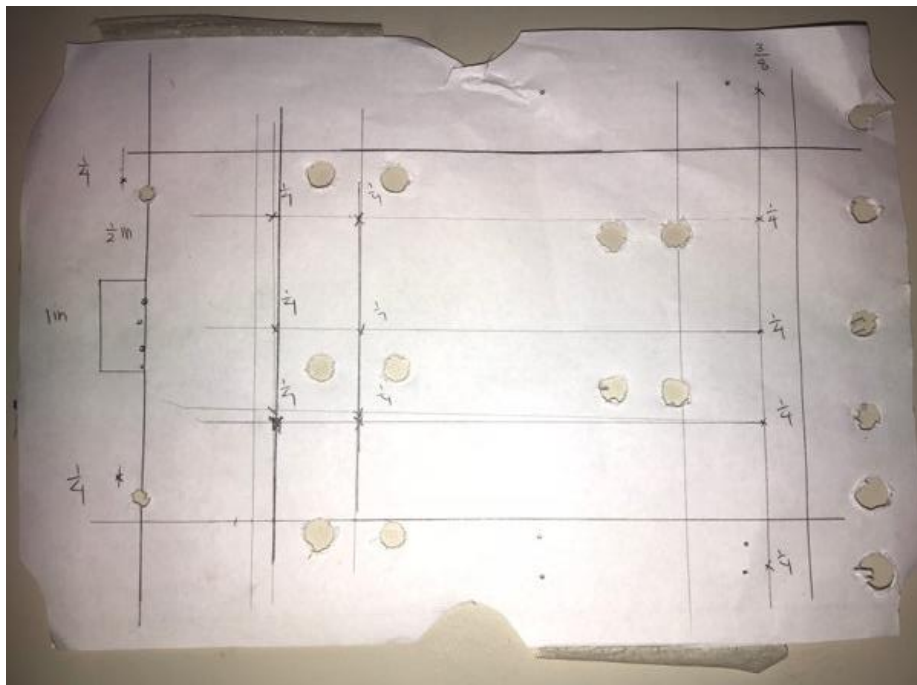


Figure 4.3: Rough makeshift stencil used to drill holes into the lid of the enclosure

An attempt to drill the lid of the enclosure was done through this stencil. It was a very crude and rather brash method to do so, but it was necessary in order to fit the screw holes of the

enclosure. The outside of the front cover does not reveal the plastic encasing that holds the screws in place.

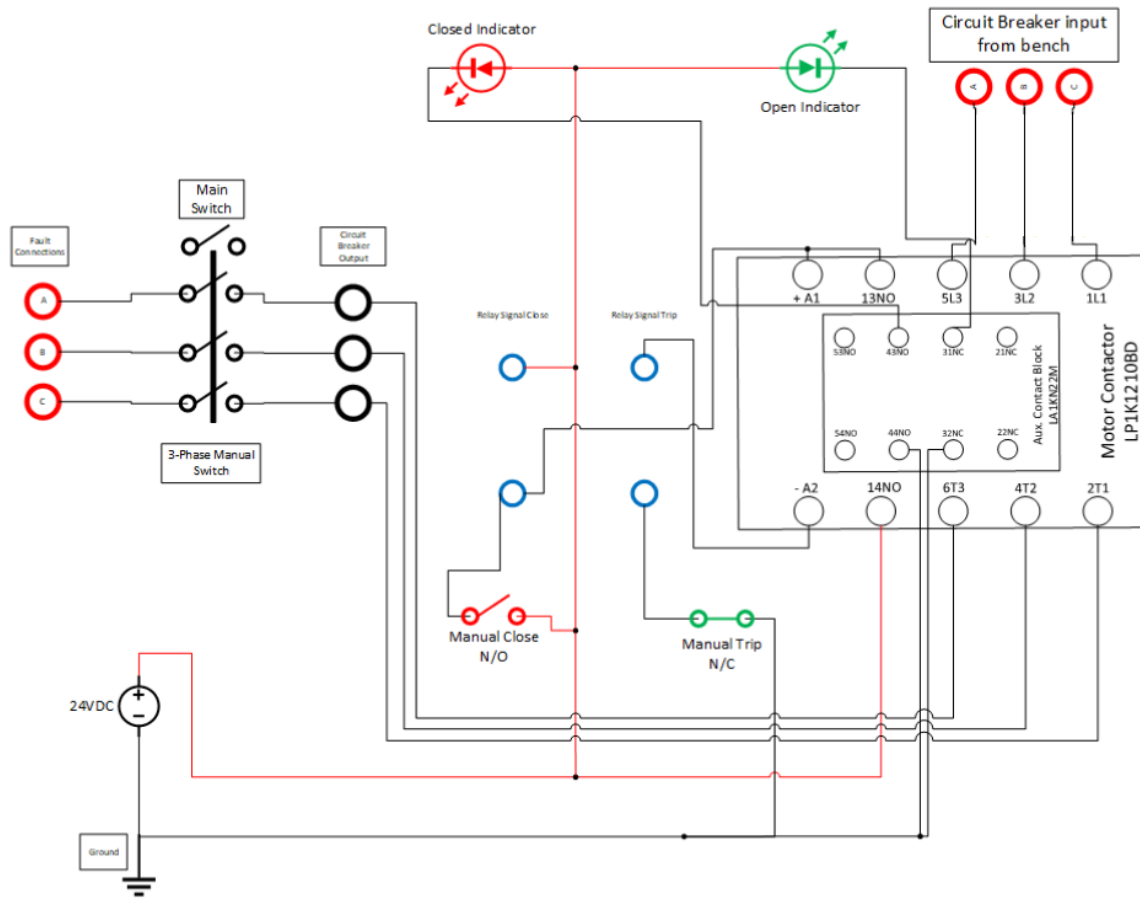


Figure 4.4: Circuit Schematic using Circuit Elements [9]

The schematic of the current circuit breaker is the same as the previous, with the only change being component placement on the faceplate of the plastic enclosure.

CHAPTER 5 - HARDWARE TESTS AND RESULTS

Building the circuit breaker requires obtaining everything from the list of materials, then drilling holes in the enclosure to fit the components inside it. The procedure of building it is as follows:

1. Drill holes to reflect the size of the components on the lid of the enclosure
 - a. A stencil was used to facilitate this procedure
2. Attach all components onto the lid
 - a. Screw in all the banana connections
 - b. Use screws and nuts to attach the mechanical switch
 - c. Attached LED's and buttons using their given design
 - d. Used red terminals for input, black terminals for fault and output connections, green for ground, and blue for trip and close signal connections.
3. Wire and crimp the components
 - a. 12 gauge wires are used for connections pertaining to the inputs, outputs and faults.
 - b. 16 gauge wires are used for the rest of the connections
4. Attach the DC jack to the chassis
 - a. This will require using an adhesive due to the thickness of the enclosure and the size of the jack, an alternative to this is to find a more effective DC jack that is more suitable for this enclosure.

FAULT TESTING AND RESULTS

After building the circuit breaker, one check that can be done to test the circuit breaker is to check for continuity. Next check is to test the LEDs and buttons by shorting the two trip terminals and grounding the chassis. Plugging in an AC adapter should cause the green LED to turn on. Pressing the manual red close button should cause the green LED to turn off and red LED to turn on. Press the manual green close button to turn on the green LED again while turning off the red LED. If the circuit breaker worked as describe then it passed the first few tests.

In order to further test the circuit breaker, the following lab procedure was adapted from the Cal Poly Electrical Engineering's Power Systems Laboratory, also known as its EE 444 course. This procedure was written by Kenan Pretzer and has been adapted into the power systems curriculum at Cal Poly [11].

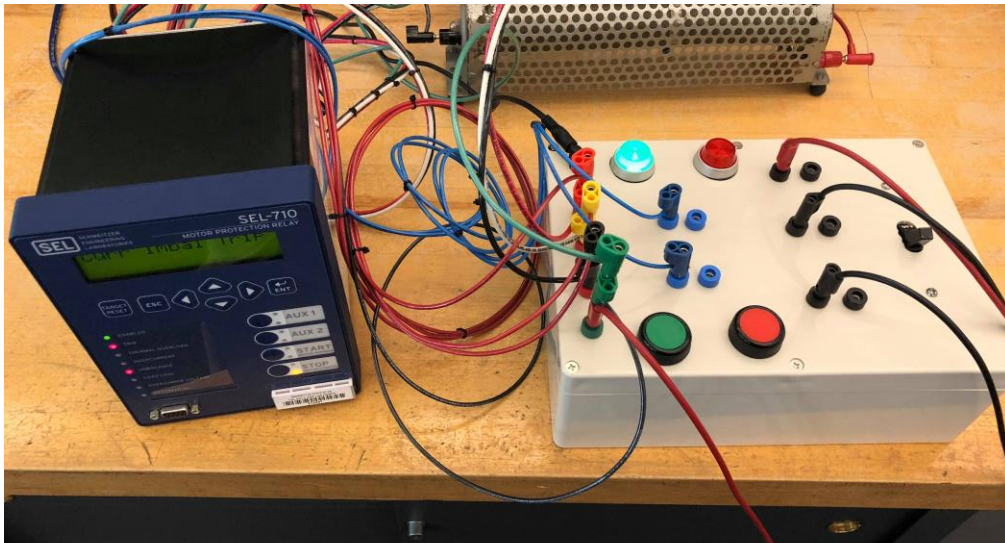


Figure 5.1: Circuit Breaker connected to the SEL-710 Relay

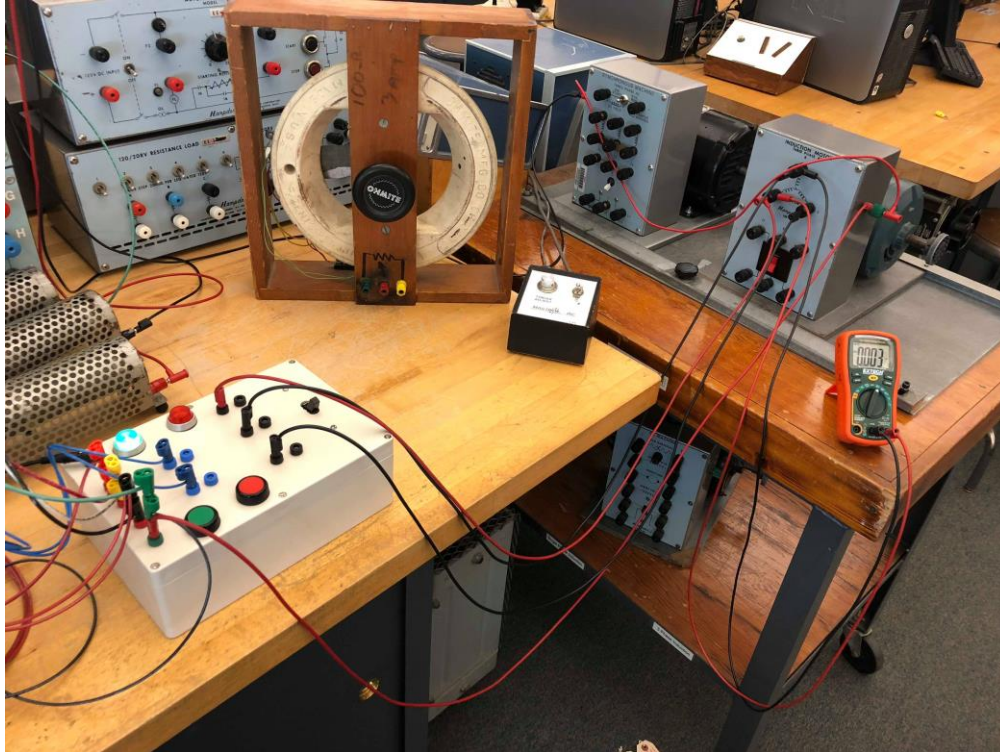


Figure 5.2: Circuit Breaker connected to the Induction Motor and Multimeter

FAULT ANALYSIS LAB PROCEDURES

List of Materials

- 25- Ω Single-Phase Power Resistor (3x)
- Bag of Banana-Banana Short Leads (2x)
- Banana-Banana or Banana-Spade Leads (18x)
- Circuit Breaker (1x)
- Computer with AcSELeRator QuickSet Software and a Serial Port
- Induction Motor: 208 V, 1/3 horsepower (1x), with Magtrol Torque-Adjust Unit (1x)
- SEL-710 Differential and Overcurrent Relay (1x)
- SEL-C234A Serial Cable (1x)
- Voltmeter (1x)

Circuit Diagram

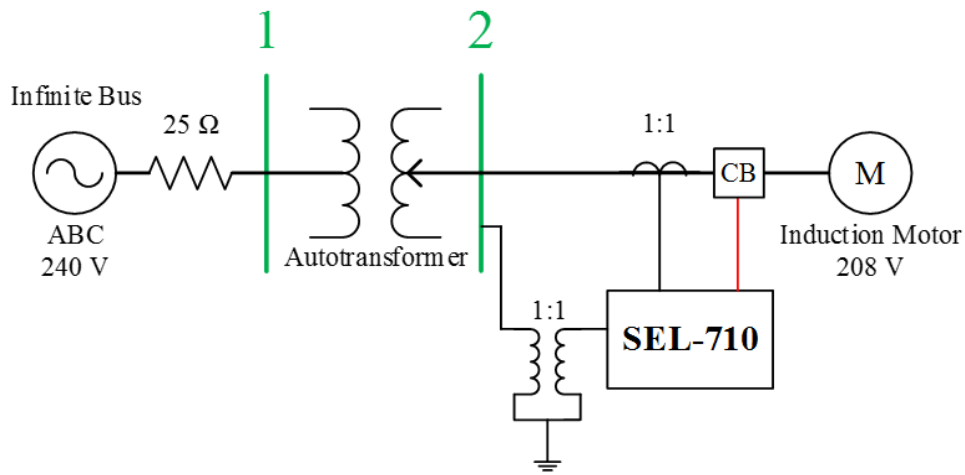


Figure 5.3 Radial Resistive Circuit Single-Line Diagram

PROCEDURE (See Appendix B for detailed procedure)

1. Plug in the power cord connected to the SEL-710 relay.
2. Connect an SEL-C234A serial cable between Port 3 on the back of the 710 and the main serial port on the back of the computer (surrounded by light turquoise color).
3. On the computer, open the AcSELERator QuickSet software.
4. Apply settings to the relay which can be found in Appendix A
5. Connect the three-phase circuit illustrated in Figure 5.4. Try to lay out the elements in the order illustrated in the schematic, so that power flows across the bench from one end to the other. This limits the number of wires crossing each other and makes the path of the current flow easier to review (and troubleshoot). Start with the sequential connection points in Table 5.2, using the diagrams posted on the wattmeter at the lab bench for assistance. Then add the following additional connections:

- a. Connect SEL-710 back-panel ports **E01**, **E02**, and **E03** to the red Circuit Breaker phase A, B, and C terminals (respectively) on the circuit breaker.
- b. Connect SEL-710 back-panel port **E05** to the green circuit breaker chassis ground terminal.
- c. Connect the green chassis ground terminals of the induction motor and circuit breaker together.
- d. Connect SEL-710 back-panel port **Z08** to the induction motor green chassis ground terminal.
- e. Connect SEL-710 back-panel port **Z07** to the green lab bench ground terminal.
- f. Connect SEL-710 back-panel port **A07** to the top Breaker Control Trip terminal on the circuit breaker. Connect the back-panel port **A08** to the bottom Breaker Control Trip terminal on the circuit breaker. These terminals correspond to the signal OUT102 in the SEL-710.
- g. Connect the positive (upper) Breaker Control 125 V_{DC} terminal to input terminal G on the lab bench. Connect the negative (lower) Breaker Control 125 V_{DC} terminal on both circuit breakers to terminal H.

Connect a voltmeter between the phase-A and phase-B terminals of the induction motor to measure the motor's line-to-line voltage.

Table 5.1 - Per-Phase Sequential Points of Connection

Phase A	Phase B	Phase C
Input Voltage	Input Voltage	Input Voltage
Bench Variac Phase A Input	Bench Variac Phase B Input	Bench Variac Phase C Input
Bench Variac Phase A Output	Bench Variac Phase B Output	Bench Variac Phase C Output
Wattmeter	Wattmeter	Wattmeter
25 Ω Resistor Input	25 Ω Resistor Input	25 Ω Resistor Input
25 Ω Resistor Output	25 Ω Resistor Output	25 Ω Resistor Output
Relay Port Z01 (Relay Input)	Relay Port Z03 (Relay Input)	Relay Port Z05 (Relay Input)
Relay Port Z02 (Relay Output)	Relay Port Z04 (Relay Output)	Relay Port Z06 (Relay Output)
Circuit Breaker Red Terminal	Circuit Breaker Red Terminal	Circuit Breaker Red Terminal
Circuit Breaker Black Terminal	Circuit Breaker Black Terminal	Circuit Breaker Black Terminal
Induction Motor Stator Terminal, Phase A	Induction Motor Stator Terminal, Phase B	Induction Motor Stator Terminal, Phase C

6. Set the induction motor Magtrol Torque Adjust switch to the “OFF” position.
7. Verify the circuit connections and obtain instructor approval to apply power to the circuit.
8. Set the variac to provide the induction motor with its rated voltage.
 - a. Rotate the variac control dial to its fully counter-clockwise position. This sets the autotransformer tap to its lowest available output voltage.
 - b. Apply both 240 V_{AC} and 125 V_{DC} (if needed for the circuit breaker) power from the bench.
 - c. Rotate the variac control dial clockwise until the voltmeter displays 208 V.
 - d. Press the “TARGET RESET” button on the front panel of the SEL-710 to clear any previous undervoltage conditions.

- e. Close the circuit breaker (with the Manual Breaker Control Close button).
Confirm that the three-phase power displayed on the wattmeter is approximately 1.5 A. If the displayed current exceeds 2 A, turn off the bench power and check the circuit wiring for errors.
 - f. The induction motor should now be running. If the SEL-710 immediately trips for an undervoltage condition, increase the value of the Undervoltage Trip Delay (**27P1D**) setting. This delay keeps the relay from tripping in response to the extra voltage drop across the current-limiting resistors due to the temporary motor inrush current. If this fails, decrease the Undervoltage Trip Level (**27P1P**) setting.
 - g. Rotate the variac control dial clockwise until the line-to-line voltage displayed on the voltmeter at the induction motor terminals again reads 208 V. This compensates for the voltage drop across the current-limiting resistors due to the additional current drawn by the induction motor.
9. Create a line-to-line fault at the induction motor.
- a. Turn off AC and DC power from the bench.
 - b. Jumper the black Circuit Breaker terminals to the red Fault Connections terminals (if present) on the circuit breaker. Jumper two of the black Fault Connections terminals together (line-to-line fault configuration).
 - c. Set the circuit breaker Fault Switch to the “Normal” position.
 - d. Turn on AC and DC bench power. Press the “TARGET RESET” button on the front panel of the SEL-710 to clear any previous undervoltage conditions.
 - e. Manually close the circuit breaker.
 - f. Flip the circuit breaker Fault Switch to the “Fault” position.

- g. Watch the wattmeter to confirm that the SEL-710 trips the circuit breaker to clear the fault. If it does not, turn off AC bench power before sustained fault current damages circuit components.
 - h. Once the relay clears the fault, turn off AC and DC bench power and flip the Fault Switch to the “Normal” position. Press the “TARGET RESET” button on the SEL-710 to clear the relay’s front-panel LED display.
 - i. Retrieve the event file from the SEL-710 (Step 27).
 - j. Add the 50P1P and 50P1T digital signals to the oscillogram plot.
10. Retrieve the SEL-710 event file for the fault trip.
- a. In QuickSet, select “Tools,” “Event Files,” “Get Event Files.
 - b. In the window that comes up, select “Refresh Event History.”
 - c. Choose an Event Type of “16 Samples / Cycle – Raw” and an Event Length of 15 cycles.
 - d. Check the boxes of the event file(s) corresponding to the fault. Event files are indexed with ‘1’ being the most recent event file saved by the relay.
 - e. Click “Get Selected Events.” Save the events in a convenient location, using either a default or custom naming convention.
 - f. Double-click on the event report file in its file path location. The AcSELERator Analytic Assistant software automatically opens an oscillogram plot of the event.
 - g. Click the “Pref” button in the lower-right corner of the oscillogram to add digital fault-trip signals to the plot. Left-click on the signal you wish to display (from the available list in the lower-left corner of the screen); then right-click-drag the signal to the Digital Axis list of signals to be displayed. Click “Ok.”

- h. After saving the desired event files, enter the “**HIS C**” command in the QuickSet Terminal window (select “Communications,” “Terminal”) to clear previous event files from the relay’s memory. If an error message appears about an invalid access level, type in “**ACC**”, the Enter key, the level relay 1 password (default for SEL-710 is “**OTTER**”), and the Enter key. Proceed to clear the event files.
11. Create a three-phase fault (not grounded) at the induction motor.
 - a. Turn off AC and DC power from the bench.
 - b. Jumper the black Circuit Breaker terminals to the red Fault Connections terminals (if present) on the circuit breaker. Jumper together the black Fault Connections terminals (three-phase fault configuration).
 - c. Set the circuit breaker Fault Switch to the “Normal” position.
 - d. Turn on AC and DC bench power. Press the “TARGET RESET” button on the front panel of the SEL-710 to clear any previous undervoltage conditions.
 - e. Manually close the circuit breaker.
 - f. Flip the circuit breaker Fault Switch to the “Fault” position.
 - g. Watch the wattmeter to confirm that the SEL-710 trips the circuit breaker to clear the fault. If it does not, turn off AC bench power before sustained fault current damages circuit components.
 - h. Once the relay clears the fault, turn off AC and DC bench power and flip the Fault Switch to the “Normal” position. Press the “TARGET RESET” button on the SEL-710 to clear the relay’s front-panel LED display.
 - i. Retrieve the event file from the SEL-710 (Step 27).
 - j. Add the 50P1P and 50P1T digital signals to the oscillogram plot.

12. Create an undervoltage condition at the terminals of the induction motor.
 - a. Turn on AC and DC bench power. Press the “TARGET RESET” button on the front panel of the SEL-710 to clear any previous undervoltage conditions.
 - b. Manually close the circuit breaker.
 - c. Rotate the variac control dial counter-clockwise to decrease the input voltage to the induction motor, while watching the motor’s terminal voltage displayed on the voltmeter. Momentarily stop once the voltmeter at the induction motor terminals reads 185 V. Proceed to slowly rotate the variac dial until the SEL-710 trips the circuit breaker. Record the approximate voltage at which trip occurred.
 - d. Retrieve the event file from the SEL-710 (Step 27).
 - e. Add the 27P1 and 27P1T digital signals to the oscillogram plot.

If the procedure is done correctly, the oscillograms should look similar to the oscillograms in Figures 5.4, 5.5, 5.6.

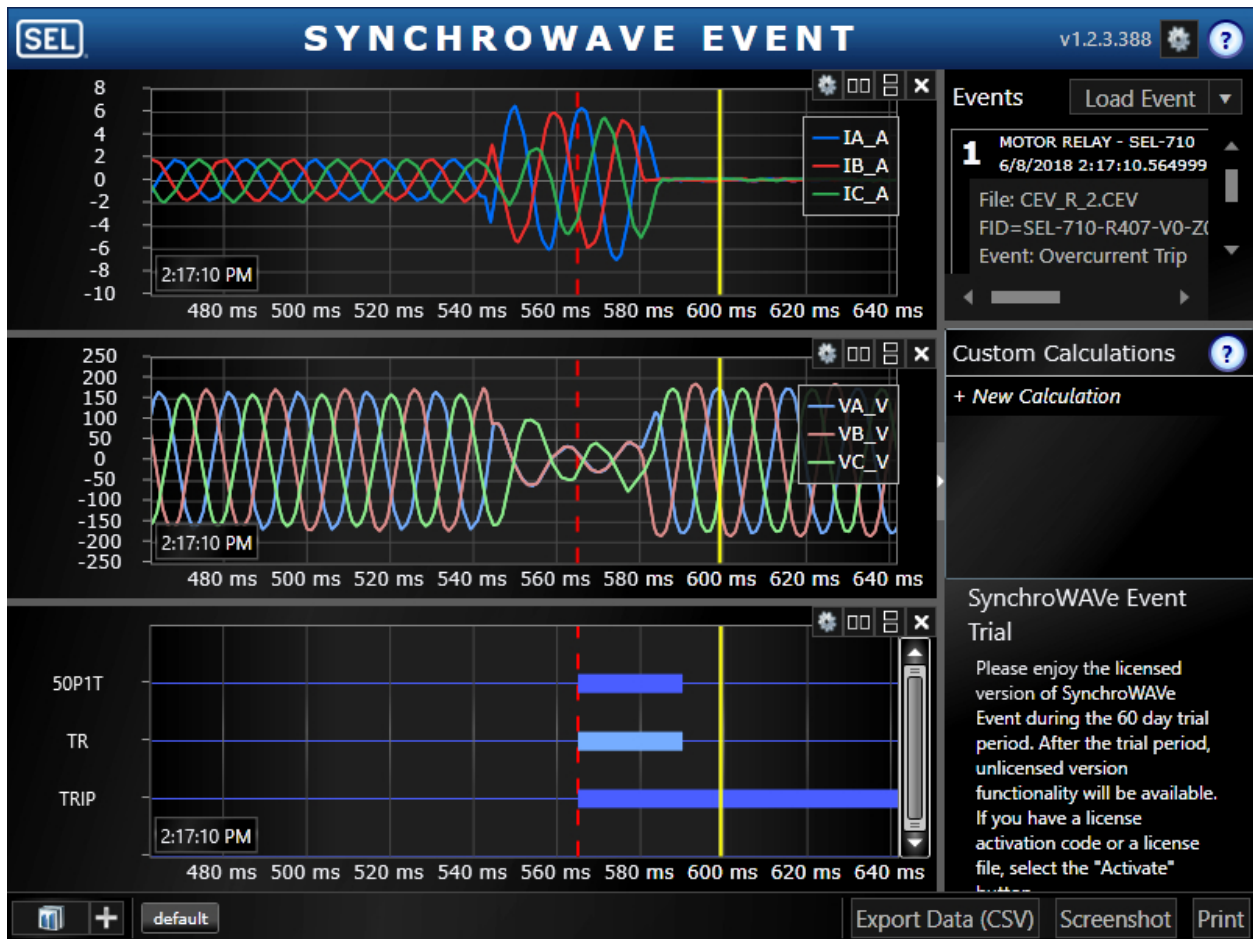


Figure 5.4: Line to Line Fault Analysis

This Line-to-Line plot shows a sudden increase in current after the 540 ms point indicating the moment the fault happened. The fault lasted for more than 40 ms and cleared before the 590 ms point.

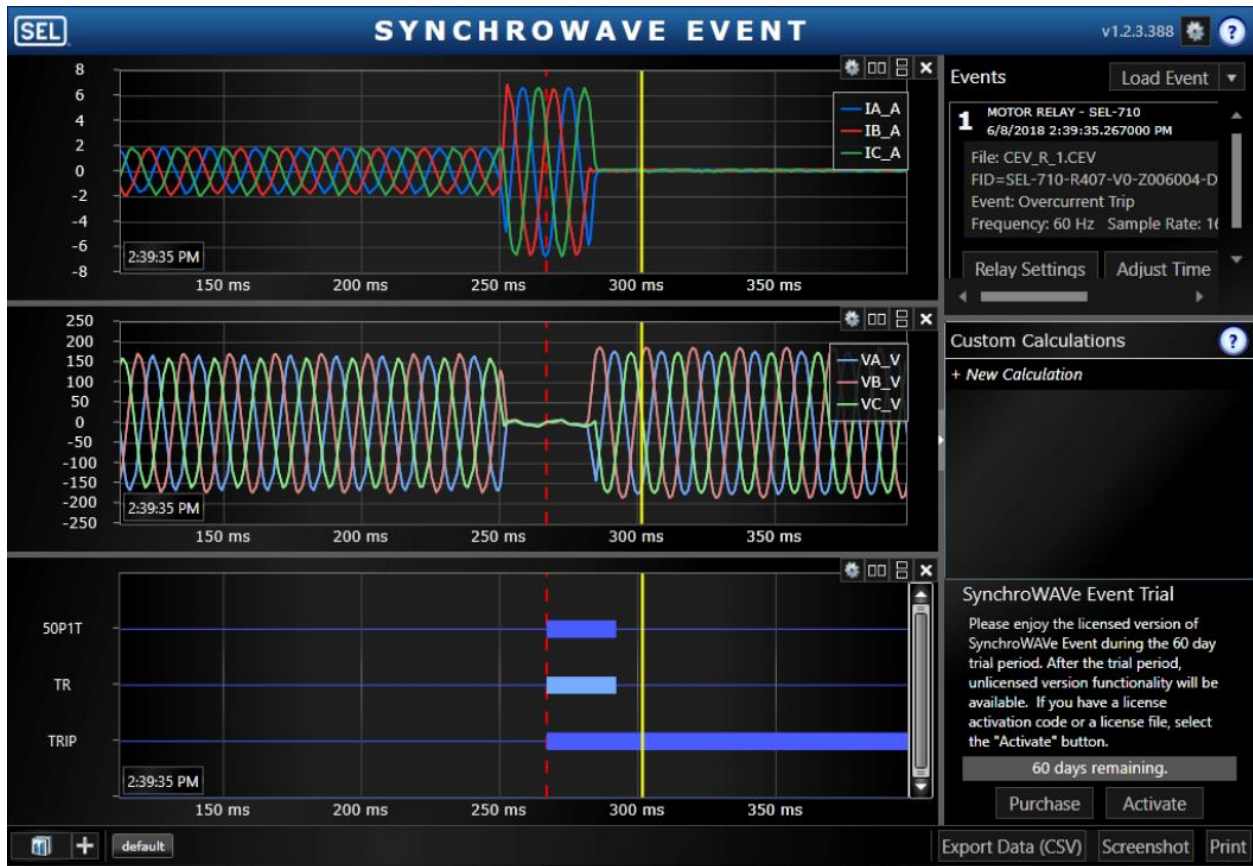


Figure 5.5: Three Phase Fault Analysis

Similar to the line-to-line fault, this 3-phase fault plot shows an increase in current at the 250 ms mark lasting a little less than 40 ms.

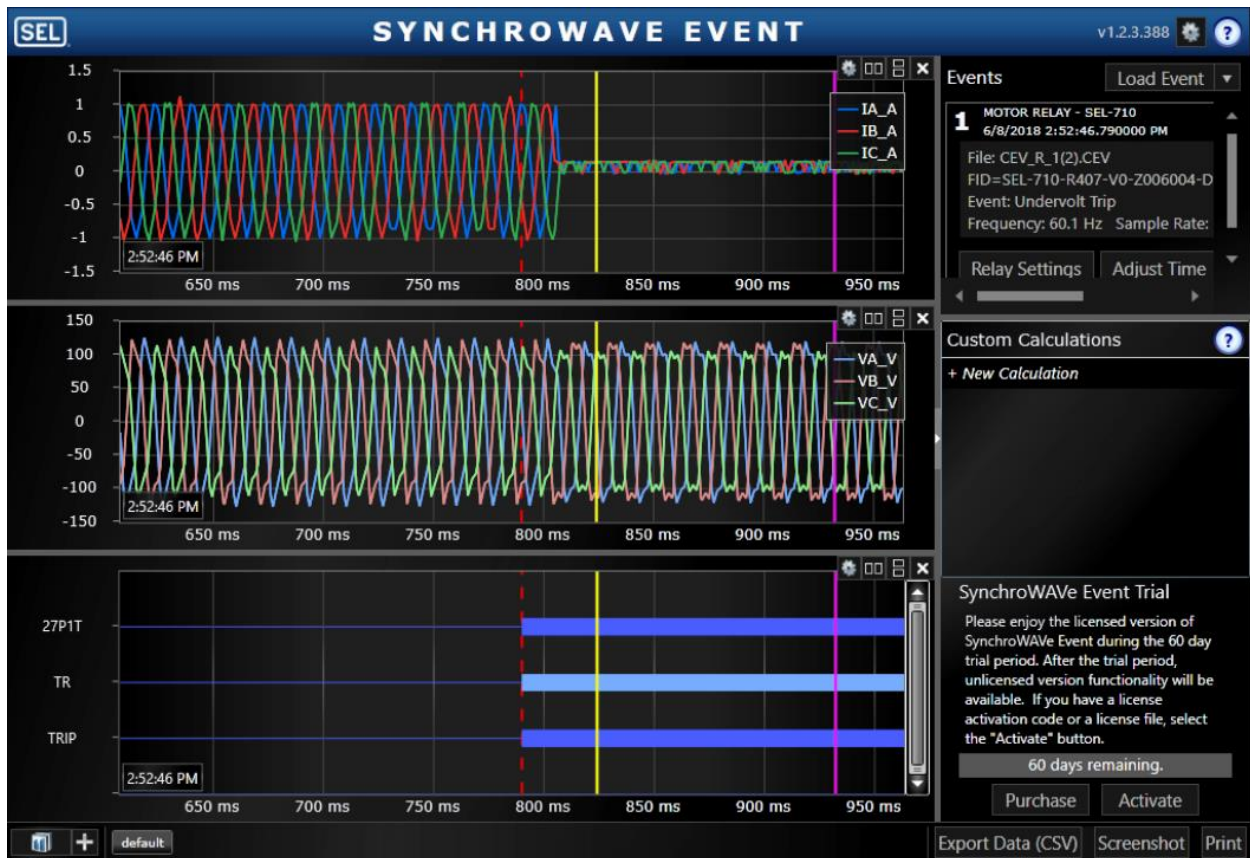


Figure 5.6: Undervoltage Trip Analysis

For undervoltage tripping, the variac was turned so that the voltage across the motor terminal slowly decreased until the undervoltage relay tripped.

These three tests confirm the functionality of the circuit breaker. If the circuit breaker did not function properly in these tests then there are several checks that can be performed. First, check the circuit configuration to make sure all components are wired correctly. Next, check the relay settings. If the settings and wiring are correct, then consider switching out the induction motor with one that has a less current rating. Before our test circuit worked, the induction motor had a line-to-line voltage drop of about 70 V with the variac turned all the way up which caused an undervoltage trip. After switching out the induction motor with one that has less current

rating, the line-to-line voltage of the induction motor was able to reach 208V. One can also troubleshoot the circuit by checking continuity and looking for major voltage drops if any.

CHAPTER 6 - CONCLUSION

Due to the inherent nature of this project, the majority of the improvements stems from component purchasing and to a lesser extent aesthetic design:

- The ground connection and DC jack can be placed on the side of the enclosure
 - Due to the original design of the experiment, the previous metal enclosure and attempted wooden enclosure was too difficult to drill into, so the attachment was found most suitable in the acrylic lid. However, with the change to a plastic enclosure, the faceplate design did not change to reflect the new material of enclosure. A future improvement would be to drill holes in the side of the enclosure and to utilize that space appropriately.
- Availability of components
 - With the primary resources of the electrical components being eBay and legacy products from other companies like Schneider Electric, the components were hard to source, and if they were sourced, a limited quantity could be obtained. A further improvement to this experiment would be to find suitable components that could be purchased en masse.
- Proper stenciling of the enclosure
 - With the limited time available to obtain and drill the enclosure, a makeshift stencil was used to measure out spots to drill holes for the components. This led to rough placement for the trip and close connections of the circuit breaker. An easy

improvement to this would be to space out the components and to measure the drilling holes more accurately to optimally utilize the plastic enclosure.

Students will be utilizing these circuit breakers in the new microgrid lab being developed at Cal Poly. To ensure that this project can be repeated and replicated, all components were sourced from websites and manufacturers that can mass produce them. Most importantly, the circuit breaker *safely* functions as intended.

Although the delivery of the circuit breaker was not the most aesthetically pleasing, it serves as a lighter, cheaper, safer, functional alternative to its predecessors. While there are improvements to be made, it is the safest iteration of the circuit breaker yet. This will be the design model for the rest of the circuit breakers made for Cal Poly, and to other schools who see this as a critical component for power systems education

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APPENDIX A - BILL OF MATERIALS

Description	Part No.	Quantity	Price Per Unit	Total Cost	Vendor
Motor Contactor	LP1k1210BD	1	\$40.45	\$40.45	Amazon
Auxiliary Contact Block	LA1KN22	1	\$14.20	\$14.20	Schneider Electric
3-Phase Manual Switch	30003D	1	\$50.00	\$50.00	Automation Direct
24VDC Laptop Charger	N/A	1	\$11.49	\$11.49	eBay
DC Barrel Power Jack	CP-002A-ND	12	\$0.58	\$6.99	Amazon
Green Button	ATI XB-22	1	\$7.95	\$7.95	eBay
Red Button	PLN-22A ATI	1	\$7.95	\$7.95	eBay
Red LED	ATI XB-22	1	\$5.95	\$5.95	eBay
Green LED	PLN-22A ATI	1	\$5.95	\$5.95	eBay
Red Banana Jacks	501-1080-ND	3	\$2.00	\$6.00	Digi-key
Black Banana Jacks	501-1078-ND	6	\$2.00	\$12.00	Digi-key
Blue Banana Jacks	501-1084-ND	4	\$2.00	\$8.00	Digi-key
Green Banana Jacks	501-1083-ND	1	\$2.00	\$2.00	Digi-key
12 AWG Wire	55671523	1	\$23.13	\$23.13	Amazon
16 AWG Wire	55668023	1	\$12.44	\$12.44	Amazon
12 AWG Ring Terminals	N/A	10	\$0.38	\$3.80	Amazon
16 AWG Ring Terminals	N/A	20	\$0.19	\$3.80	Amazon
ABS Junction Box	N/A	1	\$21.39	\$21.39	Amazon
Nuts	M5-.80	30	\$0.35	\$10.50	Ace Hardware
Screws	N/A	6	\$1.25	\$7.50	Home Depot
				\$261.49	

APPENDIX B - DETAILED PROCEDURE

1. Plug in the power cord connected to the SEL-710 relay.
2. Connect an SEL-C234A serial cable between Port 3 on the back of the 710 and the main serial port on the back of the computer (surrounded by light turquoise color).
3. On the computer, open the AcSELeRator QuickSet software.
4. Determine the current baud rate for Port 3 on the 710.
 - A. On the front panel of the relay, press the enter button, labeled “**ENT.**”
 - B. Use the down-arrow button to navigate to “**Set/Show**” on the front panel display. Press the enter button.
 - C. Use the down-arrow button to navigate to “**Port**” on the front panel display. Press the enter button.
 - D. Navigate to Port “**3**” and press the enter button.
 - E. Navigate to “**Comm Settings**” and press the enter button.
 - F. Use the down-arrow button to navigate through the current Port 3 settings. The baud rate (**SPEED**) is near the top of the list. If the baud rate is already set to 19200, press the “**ESC**” button several times to restore the screen to its normal display, and continue to the next step.
 - G. If the current relay baud rate is not set to 19200, use the following steps to change the baud rate:
 - H. With the relay’s baud rate setting highlighted, press the enter key.
 - I. Use the up, down, left, and right buttons to enter the relay’s level 2 password (default is “**TAIL**” and is case-sensitive). Press the enter key to select each letter. Navigate to and select “**Accept**” after entering the password.
 - J. Press the up/down-arrow buttons until “19200” (not 19.2) appears. Press the enter key.
 - K. Press “**ESC**” twice and select “**Yes**” to save the new port setting.
5. On the QuickSet main window (Figure B1), open the Communication Parameters window (“Communications,” “Parameters”) (Figure B2) to define and create a communication link with the 710. Enter the following information for a Serial Active Connection Type:
 - A. Device: “COM1: Communications Port”
 - B. SEL Bluetooth Device: Unchecked
 - C. Data Speed: 19200
 - D. Data Bits: 8
 - E. Stop Bits: 1
 - F. Parity: None
 - G. RTS/CTS: Off

- H. DTR: On
- I. XON/XOFF: On
- J. RTS: N/A (On)
- K. Level 1 Password (Default “**OTTER**”)
- L. Level 2 Password (Default “**TAIL**”)

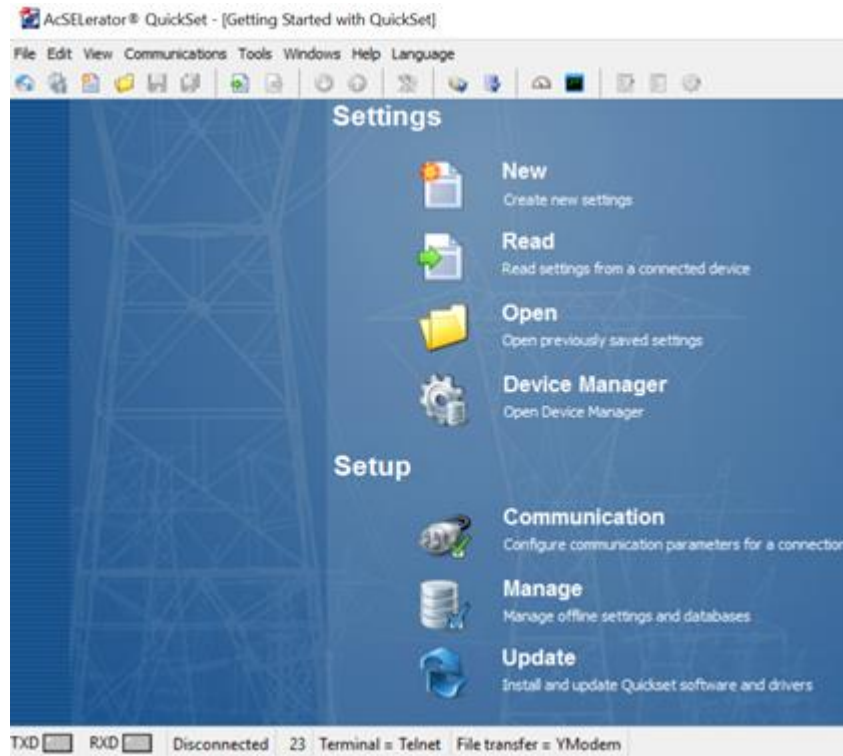


Figure B1: QuickSet Main Window

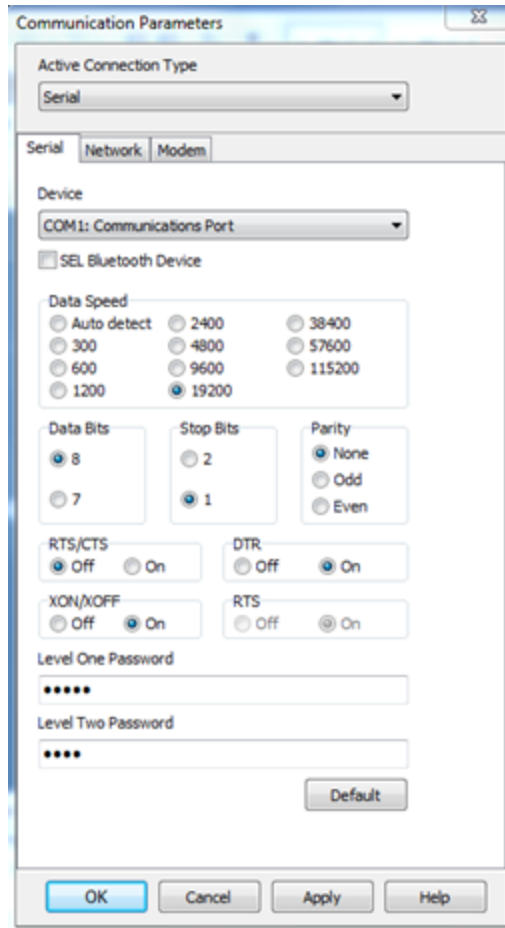


Figure B2: SEL-710 Communication Parameters Window

6. Click “Apply” at the bottom of the Communication Parameters window. Then click “Ok.” If successful, the connection status in the lower-left corner of the QuickSet main window should say “Connected.”
7. Create a new settings file for the SEL-710 relay.
 - A. In the QuickSet main window, create a new settings file for the SEL-710 relay (“File,” “New”).
 - B. Choose the Device Family, Model, and Version for this specific relay unit from the available menus, and then click “Ok” (Figure B3). Look up the relay’s version number using the front-panel interface on the relay. Press the “ENT” button, and use the down-arrow button to navigate to the “STATUS” option. Press the enter button again. Select the “Relay Status” option. Navigate down to the “FID” option. Scroll across the relay’s FID string until you come to the “Z-number.” The first three digits following the ‘Z’ are the relay version number. Press the “ESC” button several times to restore the front-panel screen to its normal display. Note: if no devices are listed in the QuickSet drop-down

menus, then the device drivers need to be installed using the SEL Compass software. Ask for assistance.

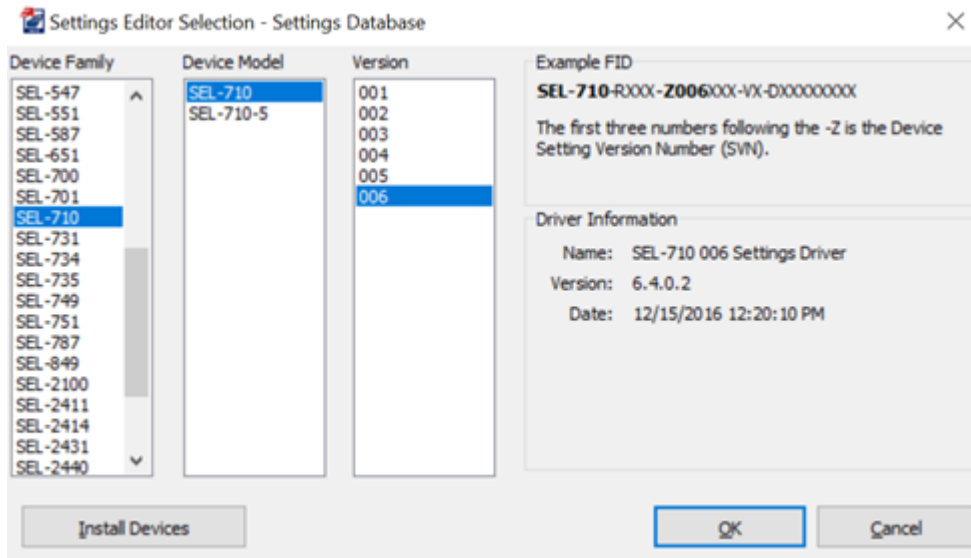


Figure B3: Identifying SEL-710 Relay Family, Model, and Version

- C. Enter the relay Part Number (Figure B4), printed on the serial number label (P/N, Figure B5) attached somewhere on the relay chassis. Note that the 5 A Secondary Input Current reflects the convention for American current transformers.

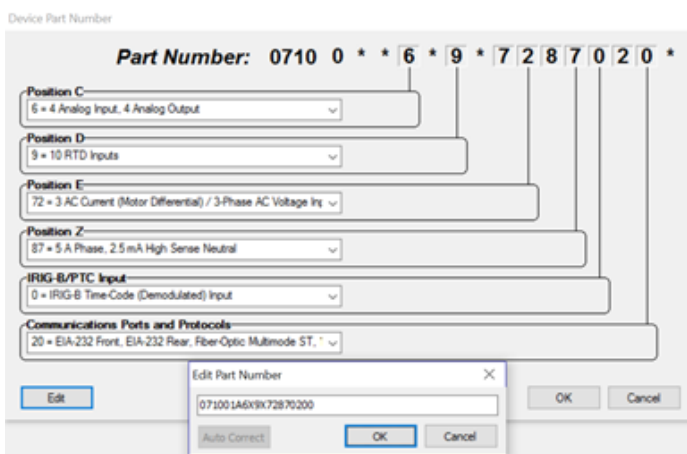


Figure B4: Identifying SEL-710 Relay Part Number



Figure B5: Example SEL-710

8. Save this relay settings database file (“File”, “Save As”; “New” if you do not want to use an existing settings database) in a location where it may be reused in future experiments. See Figure B6 and Figure B7. Then create a Settings Name for this particular settings file.

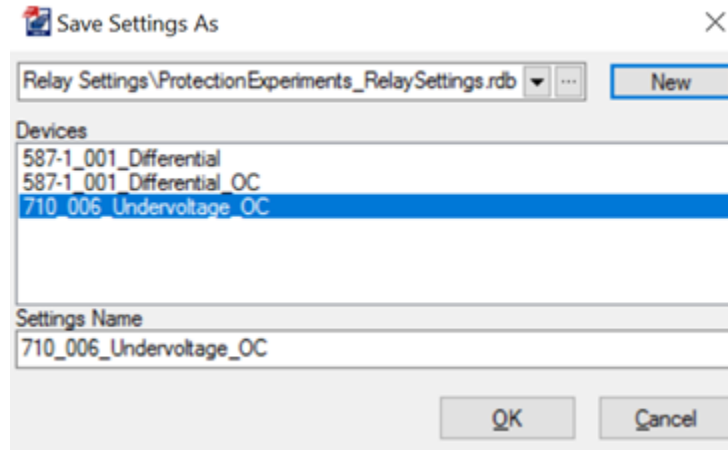


Figure B6: Saving SEL-710 Settings

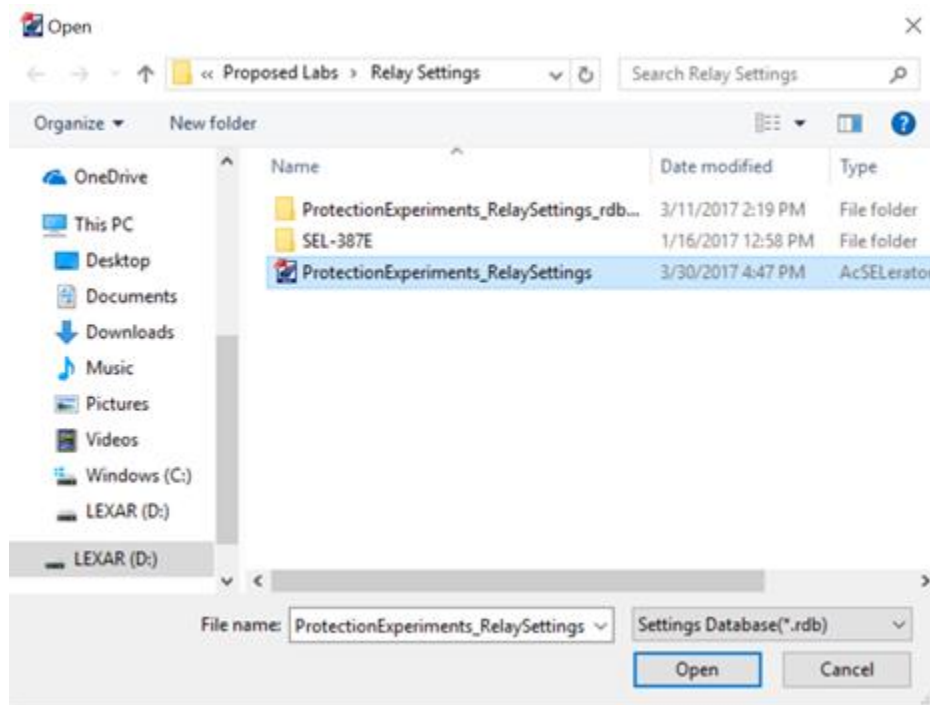


Figure B7: Choosing Location for New SEL-710 Relay Settings Database

9. Open Global settings in the drop-down menu on the left side of the Settings Editor main window (Figure B8).

- A. Under General settings (Figure B9), choose a Phase Rotation sequence (**PHROT**) of ACB. The frequency and phase rotation settings correspond to electrical properties of the utility. Replace the default Fault Condition (**FAULT**) contents with “TRIP”.

- B. Under Breaker Monitor settings (Figure B10), select ‘N’ for the Enable Breaker Monitor (EBMON) setting.

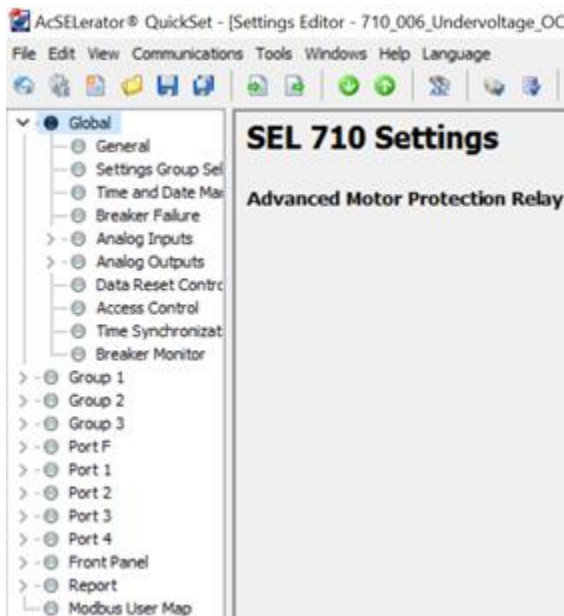


Figure B8: SEL-710 Settings Editor Main Window

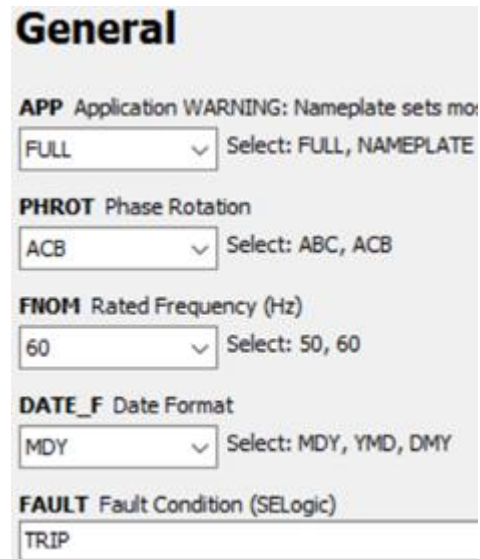


Figure B9: SEL-710 General Settings



Figure B10: SEL-710 Breaker Monitor Settings

10. Open the Group 1, Set 1 settings menu on the left side of the screen.
11. Enter the following information in the Main Settings (Figure B11 and Figure B12).
 - A. Enter a Phase Current Transformer Turns Ratio (**CTR1**) of ‘1’, reflecting the fact that the currents measured by the relay are the actual system line currents (not stepped down). Current and potential transformers are not needed in this experiment because the system line currents and voltages (even during fault conditions) are relatively low. The direct connections to the relay are modeled as 1:1 current and potential transformers in Figure 5.4 to illustrate how a relay would typically be connected in a circuit.

- B. Enter a Motor Full Load Amps (**FLA1**) value seen on the nameplate of the induction motor. This setting acts like the pickup current setting in traditional electromechanical relays, in addition to its role in multiple motor performance calculations made by the SEL-710.
- C. Enter a Neutral Current Transformer Turns Ratio (**CTRN**) of '1'.
- D. Enter a Potential Transformer Turns Ratio (**PTR**) of '1', reflecting the fact that the voltages measured by the relay are the actual system voltages (not stepped down).
- E. Enter a Nominal Line-to-Line Voltage (**VNOM**) value of 208 V.
- F. Select "WYE" as the Transformer Connection (**DELTA_Y**) for the potential transformer.

Main

RID Relay Identifier (16 characters)
SEL-710

TID Terminal Identifier (16 characters)
MOTOR RELAY

CTR1 Phase (IA,IB,IC) CT Ratio
1 Range = 1-5000

FLA1 Motor FLA [Full Load Amps] (amps)
1.6 Range = 0.2-5000.0

E2SPEED Two-Speed Protection
N Select: Y, N

CTR2 Phase (IA,IB,IC) CT Ratio, 2nd
100 Range = 1-5000

Figure B11: SEL-710 Main Settings

FLA2 Motor FLA (Full Load Amps), 2nd (amps)
250.0 Range = 0.2-5000.0

FVR_PH Full Voltage Reversing Contactor Phasing
NONE Select: NONE, A, B, C

CTRN Neutral (IN) CT Ratio
1 Range = 1-2000

PTR PT Ratio
1.00 Range = 1.00-250.00

VNOM Line Voltage, Nominal Line-to-Line (volts)
208 Range = 100-30000

DELTA_Y Transformer Connection
WYE Select: WYE, DELTA

SINGLEV Single Voltage Input
N Select: Y, N

Figure B12: SEL-710 Main Settings, cont.

12. Enter the following information in the Overcurrent Elements section (Figure B13, Figure B14, and Figure B15).
 - A. Under the Phase Overcurrent sub-heading, enter a Phase Overcurrent Pickup (**50P1P**) of 3.00 multiples of the full load amps setting. Leave the associated Trip Delay (**50P1D**) as its default value of 0.00 s.
 - B. Under the Residual Overcurrent sub-heading, enter a Residual Overcurrent Pickup (**50G1P**) of 0.50 multiples of the full load amps setting. Set the associated Trip Delay (**50G1D**) to 0.10 s.

- C. Under the Negative-Sequence Overcurrent sub-heading, enter a Negative-Sequence Overcurrent Pickup (**50Q1P**) of 0.50 multiples of the full load amps setting. Set the associated Trip Delay (**50Q1D**) to 0.15 s. Turn “OFF” the Negative-Sequence Overcurrent Alarm Pickup (**50Q2P**).

Phase Overcurrent

50P1P Phase Overcurrent Trip Pickup (xFLA)
 Range = OFF,0.10-20.00

50P1D Phase Overcurrent Trip Delay (seconds)
 Range = 0.00-5.00

50P2P Phase Overcurrent Alarm Pickup (xFLA)
 Range = OFF,0.10-20.00

50P2D Phase Overcurrent Alarm Delay (seconds)
 Range = 0.00-5.00

Figure B13: SEL-710 Phase Overcurrent Settings

Residual Overcurrent

50G1P Residual Overcurrent Trip Pickup (xFLA)
 Range = OFF,0.10-20.00

50G1D Residual Overcurrent Trip Delay (seconds)
 Range = 0.00-5.00

50G2P Residual Overcurrent Alarm Pickup (xFLA)
 Range = OFF,0.10-20.00

50G2D Residual Overcurrent Alarm Delay (seconds)
 Range = 0.0-120.0

Figure B14: SEL-710 Residual Overcurrent Settings

Negative Sequence Overcurrent

50Q1P Negative Sequence Overcurrent Trip Pickup (xFLA)
 Range = OFF,0.10-20.00

50Q1D Negative Sequence Overcurrent Trip Delay (seconds)
 Range = 0.10-120.00

50Q2P Negative Sequence Overcurrent Alarm Pickup (xFLA)
 Range = OFF,0.10-20.00

50Q2D Negative Sequence Overcurrent Alarm Delay (seconds)
 Range = 0.1-120.0

Figure B15: SEL-710 Negative-Sequence Overcurrent Settings

13. In the Undervoltage Elements, set the Undervoltage Trip Level (**27P1P**) to 0.80 multiples of the nominal motor voltage setting, VNOM (Figure B16). Increase the Undervoltage Trip Delay (**27P1D**) to 0.8 s to keep the relay from tripping due to effects of inrush current.

Undervoltage Elements

27P1P UV TRIP LEVEL (Off, 0.02-1.00; xVnm)	<input type="text" value="0.80"/>	Range = OFF,0.02-1.00 xVnm
27P1D UV TRIP DELAY (0.0-120.0; sec)	<input type="text" value="0.8"/>	Range = 0.0-120.0 sec
27P2P UV WARN LEVEL (Off, 0.02-1.00; xVnm)	<input type="text" value="OFF"/>	Range = OFF,0.02-1.00 xVnm
27P2D UV WARN DELAY (0.0-120.0; sec)	<input type="text" value="5.0"/>	Range = 0.0-120.0 sec

Figure B16: SEL-710 Undervoltage Elements

14. Under the Trip and Close Logic sub-heading, replace the default contents of the Trip (**TR**) equation with “50P1T OR 50G1T OR 50Q1T OR 27P1T OR STOP” (Figure B17).

Trip and Close Logic		
TDURD Minimum Trip Time (seconds)	<input type="text" value="0.5"/>	Range = 0.0-400.0
TR Trip (SELogic)	<input type="text" value="50P1T OR 50G1T OR 50Q1T OR 27P1T OR STOP"/>	
REMTRIP Remote Trip (SELogic)	<input type="text" value="0"/>	
ULTRIP Unlatch Trip (SELogic)	<input type="text" value="0"/>	
52A Contactor/Breaker Status (SELogic)	<input type="text" value="0"/>	

Figure B17: SEL-710 Trip and Close Logic

15. Enter the following information in the Logic 1, Slot A section (Figure B18).
- Select “N” for the OUT101 Fail-Safe (**OUT101FS**) option.
 - Select “Y” for the OUT102 Fail-Safe (**OUT102FS**) option.
 - Logically-invert the default **OUT102** signal to be “NOT START”. Logical inversion is necessary for interfacing the normally-open switch (OUT102) on the SEL-710 with the normally-open circuit breaker trip coil. This allows the SEL-710 front-panel START button to operate the Breaker Control Close contact on the circuit breaker through the relay’s rear-panel ports A05 and A06.

Slot A

OUT101FS OUT101 Fail-Safe
 Select: Y, N

OUT101 (SELogic)
 HALARM OR SALARM

OUT102FS OUT102 Fail-Safe
 Select: Y, N

OUT102 (SELogic)
 NOT START

OUT103FS OUT103 Fail-Safe
 Select: Y, N

OUT103 (SELogic)
 TRIP OR PB04

Figure B18: SEL-710 Logic 1, Slot A Output Logic

16. Repeat Steps 11 through 15 for the SEL-710 Group 2 - Set 2 and Group 2 - Logic 2 settings, with the following exceptions:
 - A. Enter a new Motor Full Load Amps (**FLA1**) value of 2.1 A.
 - B. Enter a Trip (**TR**) equation of “50P1T OR 50G1T OR 50Q1T OR STOP”.

17. Open Port F settings in the menu on the left side of the Settings Editor main window. Set the Port F baud rate (**SPEED**) to 19,200. Change the **AUTO** setting to ‘Y’. Leave all other Port F settings as their default values (Figure B19).

Port F

Protocol Selection

PROTO Protocol
 SEL Select: SEL, MOD

Communication Settings

SPEED Data Speed (bps)
 19200 Select: 300, 1200, 2400, 4800, 9600, 19200, 38400

BITS Data Bits (bits)
 8 Select: 7, 8

PARITY Parity
 N Select: O, E, N

STOP Stop Bits (bits)
 1 Select: 1, 2

RTSCTS Hardware Handshaking
 N Select: Y, N

T_OUT Port Time-Out (minutes)
 5 Range = 0-30

SEL Protocol Settings

AUTO Send Auto Messages to Port
 Y Select: Y, N

Figure B19: SEL-710 Port F Settings

18. Open the Port 3 settings on the left side of the Settings Editor main window. Set the Port 3 baud rate (**SPEED**) to 19,200. Change the **AUTO** setting to ‘Y’. Leave all other Port 3 settings as their default values.
19. Enter the following information in the Report on the left side of the Settings Editor main window (Figure B20 and Figure B21).
 - A. Under the SER, SER Trigger Lists headings, add “TRIP” to the existing contents of the first Sequential Event Recorder (**SER1**). This causes the SEL-710 to generate an event report for any of the conditions specified by the TR equation.
 - B. Under the Event Report heading, change the Length of Event Report (**LER**) setting to 64 cycles.
 - C. Increase the Prefault Length (**PRE**) data collection time to 10 cycles. This sets the amount of data saved in an event report before the relay tripped.

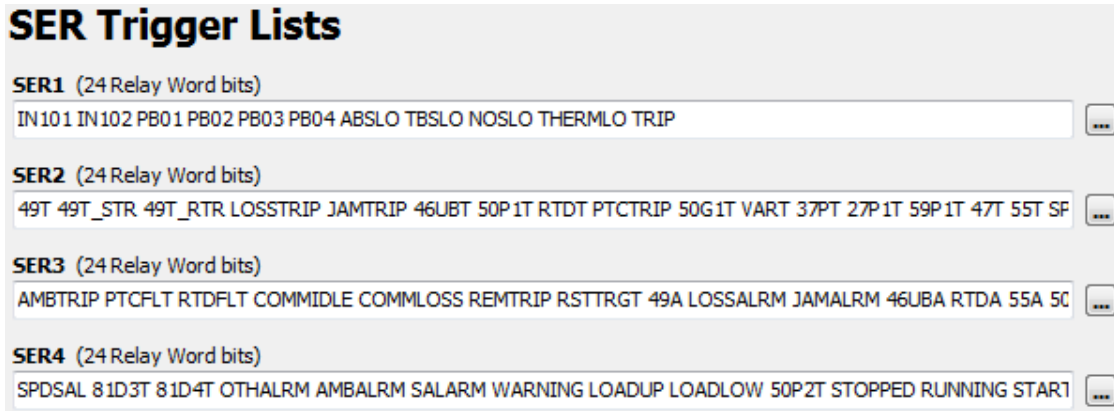


Figure B20: SEL-710 Trigger Lists Settings

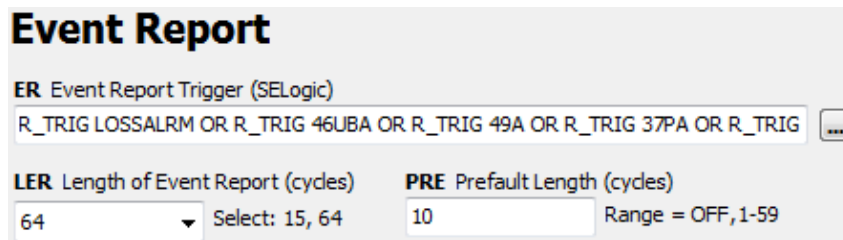


Figure B21: SEL-710 Event Report Settings

20. Save your settings (“File,” “Save”).

21. Send your settings (“File,” “Send...”) to the SEL-710. In the window that appears, check the boxes for the Set 1, Set 2, Logic 1, Logic 2, Global, Port F, Port 3, and Report settings (Figure B22). Click “Ok”. Sending only the modified settings shortens the file transfer time. Ignore any error messages associated with changing the baud rate. Since it can take several minutes to transfer the relay settings, this is a good time to start constructing the circuit.

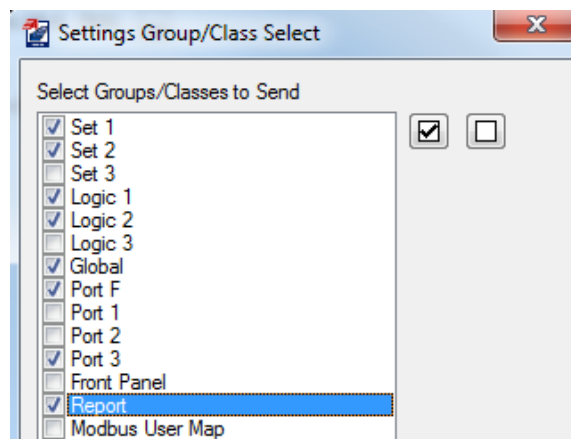


Figure B22: Send Modified Settings to the SEL-710

APPENDIX C - ANALYSIS

PROJECT TITLE: “Senior Project Design: Circuit Breaker Module”

ADVISOR: Dr. Taufik

STUDENT’S NAMES: Yei Trinh and Garvin Yee

DATE: June 12, 2018

Summary of Functional Requirements

This redesign of a circuit breaker module is meant to be used as lab equipment for the Cal Poly power systems analysis class. This allows students to simulate faults that power lines will experience without having to be around high voltage lines. This breaker can also interface with the lab’s SEL relays to see the changes in voltage and current due to the fault. This model has been redesigned with safety as the highest priority, and cost as its secondary.

Primary Constraints

The primary constraint of this experiment was time. In order to deliver the project on time, some elements of the module were rushed. The Dremel tool used to drill holes in the module’s lid was not very accurate, and a machine would have been more optimal. It was also intended for the lid of the module to be laser etched with labels instead of using a label maker to print them out. Fortunately, it only impacted the aesthetic of the module, as it still functions safely and as intended.

Economic

Please reference Appendix A for the Bill of Materials.

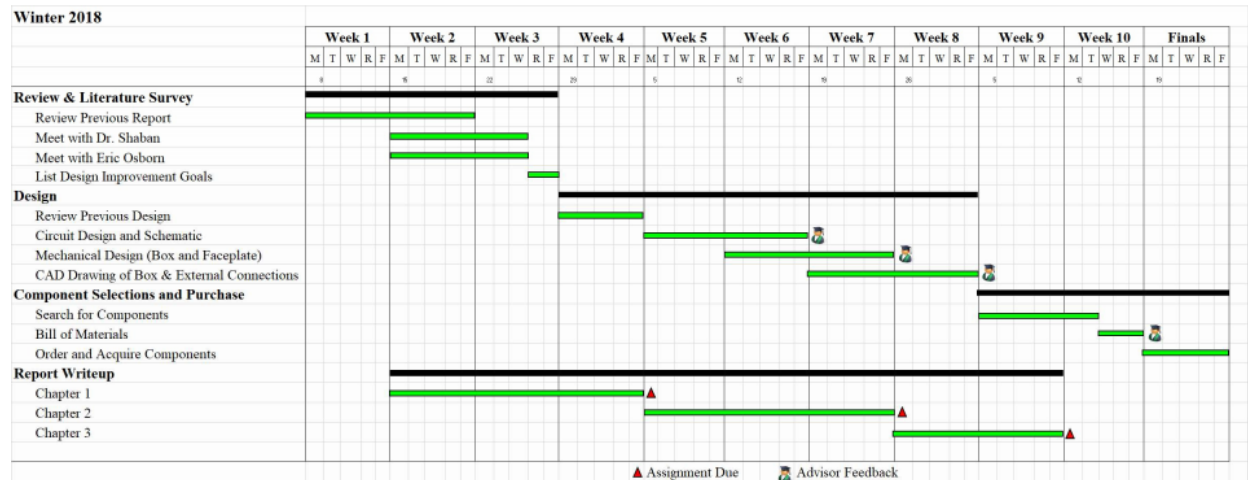
This circuit breaker took approximately 6 hours to produce, considering wire cutting, enclosure hole drilling, and assembling. The cost of this module ended up being around \$270, increasing from the previous model’s. While the predicted cost was around \$200, the actual cost ended up being slightly more. The reason for this is because all products were not donated or found via the school, and were sourced online at sites like Amazon and Digikey. This ensures consistency when reproducing the module, as the components can now be found in areas where they are mass produced.

Most tools used to complete this project were found in the Cal Poly Electrical Department’s Student Project Lab, where it had a Dremel for drilling, a wire cutter and crimper for wire management, and banana to banana cables for module testing. The department also compensates \$200 per student working on the project.

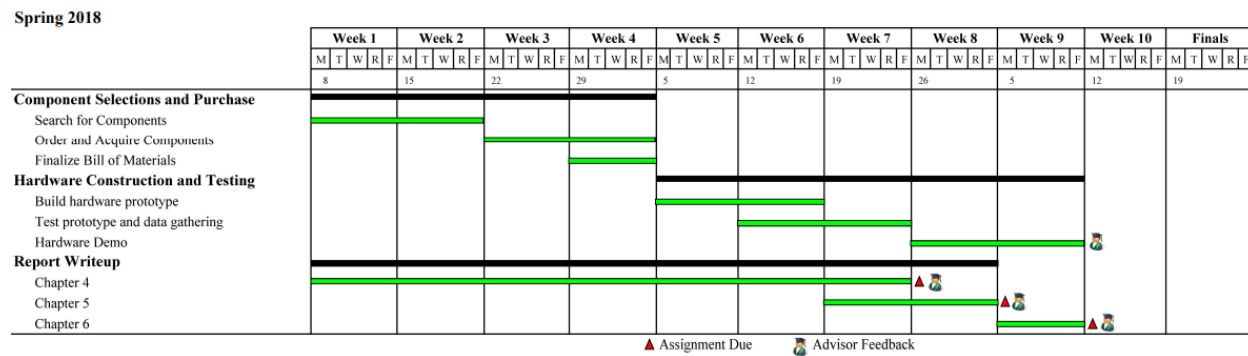
The impact of the product is seen in all of its metal and plastic components. All these components are harmful to the environment and have damaging life cycles from production to

disposal. On top of that, this product only serves as an educational tool in college laboratories, so there is no profit in making it aside from investing it in students' educations.

Garvin Yee and Yei Trinh



Trinh and Yee



Gantt Charts for the Circuit Breaker Module

If manufactured on a commercial basis

This device is not intended for commercial use and is only meant for laboratory use. There is no purchase price, profit or cost to operate. The only cost is the \$265 used to produce the module.

Environmental

This module will be used in the power systems laboratory emphasizing microgrids, where they will be drawing power from Pacific Gas and Electric Company's grid. This circuit breaker will only be drawing electricity from the grid in low quantities, so it will have little impact in the environment, natural resources, and ecosystems.

Manufacturability

Challenges in manufacturability lie in the availability of the products. Some of the components were sourced on third party sellers like Amazon and eBay. In terms of constructing the module, drilling and wiring may provide a slight challenge, but it is minimal.

Sustainability

Maintaining the device can be done by replacing components as they break down. However, due to the nature of this modular circuit breaker, unscrewing the enclosure and finding a replacement part is a simple fix for this issue.

This circuit breaker module also does not draw from any sustainable sources, as its components are plastic and metals.

Design improvements could be made in taking advantage of the size of the chassis. Due to previous design constraints, all the inputs and outputs are on the lid of the enclosure. One can improve upon the design by drilling holes in the sides of the enclosure for the DC power jack and the ground jack, leaving more space for the banana connections and the mechanical switch on the lid. The only challenge this would provide is accurately drilling into the side of the enclosure, which would be slightly harder to measure out.

Ethical

This module is meant for college laboratory use exclusively. A college student has a chance of abusing this knowledge that s/he learns in the power systems industry. Using this module for anything other than its intended purpose would be extremely dangerous.

Health and Safety

Production of the module requires drilling plastic and the use of wire cutters. The heat from drilling plastic creates a small amount of emission which is hazardous, so one must be in a well-ventilated area when drilling the enclosure. Also, one must practice safety when using the sharp tools.

Heat can also come from testing the circuit breaker. A student may come in unknowing contact with high voltage, so standard electrical lab safety must be practiced as well.

Social and Political

The module will be used to teach students about fault analysis in power systems, it will impact both instructors and students at Cal Poly. The instructors and the Electrical Engineering Department are responsible for the product. They gain the benefit of having affordable, controlled lab equipment. If this module breaks, the older models would be used, which could have an impact on students and their lab results.

The Electrical Engineering Department will also be the entity determining the usage of this module, so they have ultimate control over it.

Development

Learning how to use a Dremel and its various drill bits was independently learned in order to complete this project.