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Lab-Scale Circuit Breaker Module for Power System Laboratories

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Abstract

In this project, a circuit breaker that can simulate different types of power system faults is redesigned, constructed, and tested. They will then be implemented in power systems laboratory courses at Cal Poly. The project's goal is to improve a previous circuit breaker design to help students better visualize how faults affect power systems in the real world. Two main improvements are made to the previous circuit breaker design. The first improvement is to power the breaker with a typical wall outlet adapter instead of the DC source from the Cal Poly power systems laboratory test benches. This lets the circuit breakers be used in settings other than at Cal Poly. This also reduces manufacturing costs for the circuit breaker to allow the Cal Poly EE department to afford more modules for increased student use. The adapter converts the AC wall voltage to a lower DC value than the test bench to allow for lower voltage ratings and thus lower costs of each component. The second improvement is to redesign the faceplate layout to appear more intuitive and linear by rearranging, connecting, or removing certain terminals. These changes allow students to more easily understand how current flows through the circuit breaker and makes wire setup and troubleshooting simpler. After the final circuit breaker was constructed, testing determined correct breaker functionality, and the circuit breaker can be replicated and used at reduced costs in future Cal Poly Electrical Engineering Labs.

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1. Introduction

Power systems date back to 1882 when Thomas Edison and his company, The Edison Electric Light Company, developed the first steam-powered electric power station. Previously, there were no practical ways to bring electric lights into the home. Edison developed a system that needed an elaborate network of underground wiring and tubes (conduits). This piece of his system was quite expensive and people were skeptical about letting him dig up the street to install it [1]. However, Edison got the system working and lit the streets of New York purely on electrical power, marking the start of the power systems industry. He needed to find a way to monitor how much power each customer used. He eventually did this using an existing device that measured current and calculated the amount of power based on that current over a period of time. The station contained six generators driven by steam engines that could power 1,400 light bulbs [1]. Customers were connected to the plant by copper wires that ran underground. Later, the system was changed to the overhead system still used today due to its increased cost effectiveness. The initial station was a DC (direct current) system and operated at a single voltage. However, since DC is not easily transformed to the higher voltages necessary to minimize power loss during long distance transmission, the system was changed to AC (alternating current) and utilized a modified version of the first transformer that was suitable for power system use, which was designed by Lucien Gaulard and John Dixon Gibbs. This transformer had a few issues such as connecting the primaries in series, but these problems were corrected by William Stanley who connected them in parallel instead. Eventually, George Westinghouse set up a multi-voltage AC transformer system that competed with Edison's initial system. In 1891, a 20kV, 176 km three-phase transmission line was developed for the Electrical Engineering Exhibition in Frankfurt [2]. After a long decision-making process in 1895, it was decided that AC transmission was the better system. From there, Westinghouse built a generating station at Niagara Falls, and General Electric built a three-phase AC power system to supply Buffalo at 11kV. Later in 1936, the first experimental HVDC (high voltage direct current) line using mercury arc valves was built; however, the system was not reliable [3]. In the early 1970s, solid-state devices became the standard in HVDC. These systems and equipment guided the early history of the power systems industry and continue to be important points of reference today.

As power systems continue to grow, there are some new challenges that must be faced. One such challenge is in finding alternate sources of generating energy. In particular, we need to commit in meeting today's electricity demand without compromising the needs of future generations. This leads to the solution of pursuing renewable energy generation such as solar, wind, nuclear, and hydro. However, these new technologies come with their own complications. A number of the renewable energy sources tend to be dependent on weather fluctuations which introduces uncertainty in generation output [4]. Solar technology, for example, utilizes the sun as a power source, meaning generation cannot occur during nighttime or during weather conditions that block sunlight. The variability and uncertainty can be dealt with by switching in fast-acting,

conventional reserves as needed through utility-scale energy storage systems. Currently, the renewable variability is handled by ramping conventional reserves up or down, but as renewable energy generation grows, storage will likely become more cost effective and necessary [4].

Another challenge in modern power systems is the increased complexity in their protection system. With small power systems, protection is relatively manageable and easily maintained. However, as power systems grow and more technologies are incorporated, the protection system consequently becomes more complex. Power system protection serves to minimize the damage of equipment when a system imbalance occurs. The primary cause of damage is electrical short circuits which are referred to as "faults." Different types of faults exist in a three-phase power system such as line-to-line, three-phase, single-line-to-ground (SLG), and double-line-to-ground (DLG) faults.

To help attain effective and optimum protection system, models of physical equipment must be constructed. The digital era further allows computers to model the systems and make the necessary calculations faster than humans would [5]. There are a number of different types of equipment used to protect systems. Two important pieces of equipment are relays and circuit breakers. Relays are switching devices used to control the path of electricity. Instead of manually using a switch, a relay is controlled by a low power signal and assures complete electrical isolation between the controlled and control circuits [6]. A circuit breaker is an automatic switch, which is an on-load device, designed traditionally using electromechanical techniques to prevent power overload damage or short circuits. Once a fault is observed in the circuit, such as an overload or a short circuit, the switch is triggered and the current flow is discontinued. Relays can be included in circuit breakers but can also be separate. These devices are important for keeping the power system in working condition.

Due to the increased complexity of modern power systems with their associated technologies and protection, it becomes critical to train future power engineers to understand the circuit theory and device functionality necessary to maintain and operate a power system with adequate protection. To receive this training, many universities teach power system analysis and design courses. However, in terms of power system protection, a university could most effectively teach students using hands-on models that simulate power systems in a laboratory setting. This would allow students to be more prepared to enter a career in the power systems industry with a full understanding of basic power system protection, how it operates, and how to improve it. To better simulate a real-world system, one option is to make a microgrid system within a laboratory room. This would require equipment such as solar cells, other power generated from the grid, transmission lines, relays, and circuit breakers. With these tools, students should have the ability to recognize all types of faults, simulate them, and know the effects of each fault configuration on the power system. Since microgrids are small replicas of the full power grid, they are important tools for students to visualize and practice with the operation of power systems that exist in the real world but in an environment where making minor mistakes will not disrupt or endanger real customers and critical equipment. A microgrid laboratory course would provide students with practical experience in power system protection

design and in implementing various protection devices such as digital relays.

2. Background

The origins of this project stem from the senior project of Ozro Corulli in 2013, who created an additional lab experiment for motor protection for the Cal Poly Power Systems course, EE 444. The lab experiment covered topics such as relay setup, relay programming, and developing protections schemes for various protection scenarios. Equipment for the lab experiment included the SEL-710, a microprocessor-controlled protection relay that can read voltage and current levels of lines feeding a motor [7]. The relay can detect when an irregularity occurs and sends a signal to a circuit breaker box to open the circuit. The circuit breaker was designed and developed by Ozro Corulli as a side project using funding from Cal Poly and donations from Schweitzer Engineering Laboratories and Schneider Electric. His design allowed for the circuit breaker to interface with the lab experiment setup, as well as allow students to visualize the operation of various fault conditions. His lab experiment required the use of only one circuit breaker per lab group, leading him to produce seven circuit breakers total - one for each bench. Ozro Corulli's lab concept has been expanded upon for the presently on-going Master's thesis of Kenan Pretzer, as well as the senior projects of Ian Hellman-Wylie and Joey Navarro. Their projects aim to create a new microgrid protection lab course for Cal Poly using additional Schweitzer Engineering Laboratory equipment. Each of their projects requires the use of several circuit breakers per lab group. This senior project focuses on reproducing and redesigning the circuit breakers in order to address several problems encountered in Corulli's circuit breaker design.

One problem this senior project will address is the current lack of circuit breakers to allow all lab groups to set up and experiment with various fault types within the microgrid. The future lab course will utilize up to three circuit breakers per lab group, meaning several more must be made to allow multiple groups to perform lab experiments at the same time. With only the seven circuit breakers that are currently available, we will only be able to conduct very limited number of concurrent experiments in the future EE 444 or the microgrid lab course. Therefore, one of the goals of this project is to construct approximately 12-15 more circuit breakers. This amount should accommodate multiple lab groups for most lab experiments. If more circuit breakers are required, then future students can continue producing them using documentation from this senior project.

The Cal Poly Electrical Engineering Department is currently enhancing the hands-on laboratory experience in their power program. The overall microgrid protection lab being developed by the previously mentioned students will provide future electrical engineering students concentrating in power systems the opportunity to conduct more laboratory experiments in power systems and protection theory. The microgrid lab is being designed to help students visualize concepts covered in lectures, which is a rare but increasingly necessary tool for students in the power systems field. Although the Cal Poly EE 444 course covers topics such as power control and protection relaying, another lab is necessary for students to learn the ever

changing power systems and their relevant concepts. The lab provides increased exposure to visual, hands-on learning experience in the power curriculum at Cal Poly, and the circuit breaker design is a critical component in the microgrid lab plan. The main strength of the circuit breaker design is its ability to allow students to test and visualize various fault connections while also learning to use modern microprocessor-based relays for power system protection. To achieve these goals, the redesigning of the faceplate of the existing circuit breaker module and proper placements of terminals for external connections from and to the circuit breaker module will be some of the main focus for this project.

One idea to improve from the present circuit breaker design is the removal of superfluous inputs and outputs on the circuit breaker. A major concern with the proposed protection and microgrid lab experiments is that they require 30 or more connections. This presents a logistical problem because the electrical engineering department at Cal Poly has a limited number of short leads and banana-to-spade leads. Therefore, the new circuit breaker design will have fewer external connections to minimize the number of leads used for each new experiment.

Another improvement from the current design is to provide the DC power supply through an AC-to-DC adapter connected directly from a standard wall outlet. This will not only minimize the number of required leads to check out from the senior project window, but also it will be safer and more convenient to use during the lab setup time, allow the circuit breakers to be used anywhere outside of the lab room, and lower the cost of the circuit breaker components.

In order to design and construct an improved version of circuit breaker module, specific literature must be reviewed. The main document referenced for this senior project is the senior project report written by Ozro Corulli, who created the first set of circuit breakers for his senior project. His report provides invaluable data including an extensive list of parts used, his process of designing the faceplate, the internal hardware configuration, and lastly the assembly process of all the components in his final circuit breaker. The information provided has greatly helped accelerate the design process improvements.

Other literature on circuit breakers includes the textbook “Power System Analysis and Design” by Overbye, Glover, and Sarma. There is a section in the book devoted to how to connect different fault types, which will be useful when testing and using the circuit breaker [8].

Considering the planned changes for the circuit breaker, the overall objective of this senior project is to help streamline and improve the circuit breakers and to help with the development of new lab course to enhance Cal Poly’s power program. Furthermore, the most important objective is to ensure that students learn power system protection in a safe environment. To achieve this goal, the planned improvements include:

- Build 12-15 more circuit breakers
- Remove superfluous external inputs
- Replace DC source with wall plug
- Rearrange faceplate

3. Design Requirements

Figure 3.1 shows the level 0 block diagram for the proposed circuit breaker module. It simply shows the inputs and outputs into the circuit breaker.

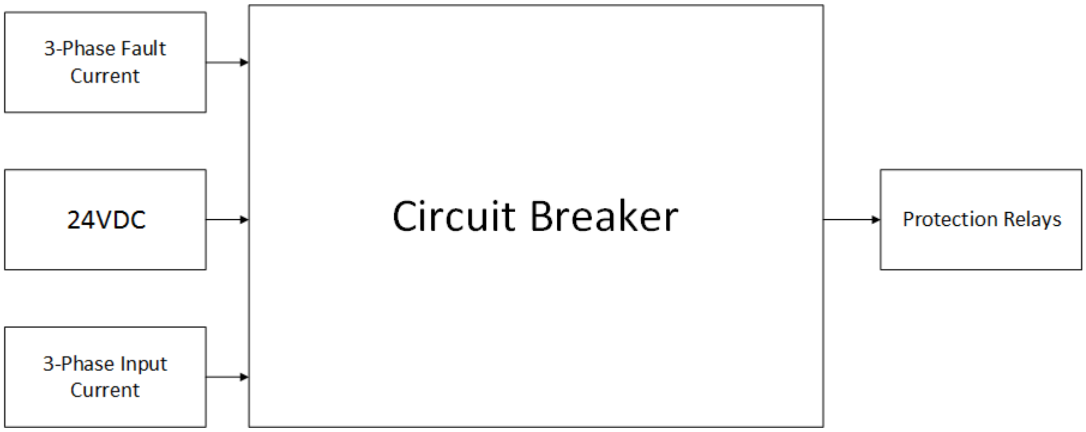

Figure 3.1: Level 0 Block Diagram

Figure 3.2 shows the level 1 block diagram for the circuit breaker. It shows the inputs and outputs as well as the basic internal connections and parts within the circuit breaker. As shown, there are three inputs: power, three phase current input, and fault input. Only one output exists which is to the protection relay. Within the breaker, there will be a mechanical switch, a three phase motor contactor, indicator LED's, manual close and trip buttons and relay contacts.

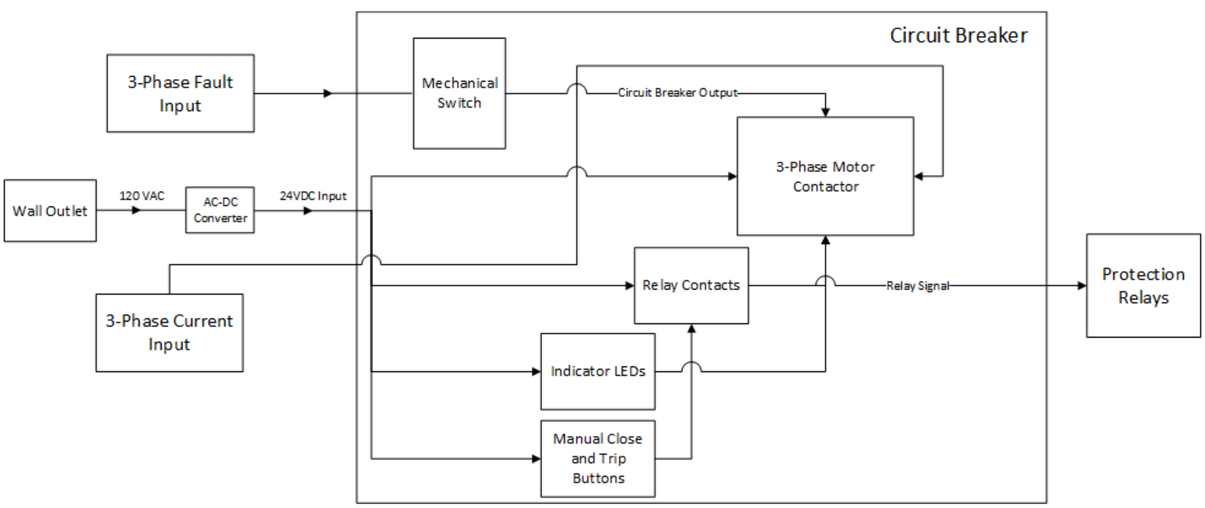

Figure 3.2: Level 1 Block Diagram

For this project, there are 6 design objectives that need to be met in order to successfully complete this project and improve from the previous breaker module design as listed below:

1. Lab bench DC input voltage removal for minimizing the number of manual physical connections to operate the module
2. Banana jack removal for simpler connection
3. Faceplate rearrangement for clearer and cleaner cable connections
4. Construction of 12 to 15 breaker modules
5. Lower the total cost of each breaker

Overall, the above purposes aim to streamline the existing circuit breaker modules so that the new modules will be more intuitive to use and will cost far less. These changes will also allow more flexibility in terms of where the modules are going to be used. The justification for these design goals is further detailed in the proceeding paragraphs.

The removal of the DC Bench voltage is a crucial parameter that would benefit the overall project the most. Currently, the circuit breakers are powered by 125VDC from the lab bench in the power systems lab 20-102 at Cal Poly. However, this setup is unique to this lab and thus will not work in any other lab room unless a 125VDC power supply is available to use. The goal is therefore to remove the dependence on the unique lab bench setup by powering the circuit breakers using a standard 120VAC outlet. The use of the standard AC outlet to replace the 125VDC supply will make the circuit breaker module more accessible to any lab beyond the power lab at Cal Poly building 20 room 102. To utilize the standard AC outlet, the DC voltage into the module can be provided by the commercially available power adapters or chargers. These adapters or chargers are a cheap and readily available component that can be used to convert 120VAC to 24VDC. Furthermore, since 24VDC is now being used in place of 125VDC, the internal electronic components would be cheaper due to the lower DC operating voltage. Using these chargers will also reduce the space requirement of the breaker module since the AC-DC conversion takes place outside of the breaker module box, and thus increasing the usable space inside the breaker module.

In addition to removing the DC power inputs from the lab bench, 3 inputs to the present breaker module are also being removed. The connections bridging the “Circuit Breaker” side with the “Fault Connection” side are no longer necessary. Instead of using short leads to connect the two sides, the two sides will be internally connected. In total, 5 inputs will be removed: 2 inputs coming from the bench and 3 inputs connecting the circuit breaker side to the fault side. This in turn will simplify the external physical cable connection.

Due to the removal of these inputs, the faceplate must also be rearranged from its present design. The current faceplate layout is not as intuitive as desired, and the interior of the housing is not space efficient. Rearranging the top faceplate will allow for more space inside the housing. The new breaker module will also be designed to be more space efficient and will provide a layout that is more intuitive for users. This could prevent confusion when wiring is applied to the circuit breaker, which may result in less damage being done to the internal components due to improper wiring.

Although many changes are being made to the circuit breaker design, the cost of each circuit breaker should be reduced. Currently, the circuit breaker is capable of managing upwards

of 30A and 660VAC. Due to the change in power supply from 125VDC to 24VDC, the parts being used for these new breakers are going to be rated for lower amounts. For instance, the current design uses a 125VDC Motor Contactor that costs approximately $106. The new design will use a motor contactor of 24VDC that costs about $50 per contactor. For the construction of 15 breaker modules, this reduced cost presents a savings of $840. The manual switch is also being changed to a lower rating in order to save money. The $135 switch is going to be replaced with a $50 switch. With a savings of $85 on each switch, the total amount saved on 15 switches is $1275. These savings allow more additions for improvements or breaker modules.

The final design requirement was the construction of 12-15 circuit breakers. In the Power laboratory at Cal Poly building 20 room 102, there are a total of 8 benches with one being dedicated for senior and master's thesis projects. Thus with the remaining 7 lab benches, the final goal for this senior project is to get at least 2 circuit breakers constructed for each bench. This would leave 1 or 2 spare circuit breakers that could be used as replacements when needed.

Since the proposed module will use 24VDC to power internal electronics, the LEDs and 3 phase motor contactor must be rated for this voltage. The normal operating current of the system is on the order of microamps, and most LEDs and motor contactors should already be rated well above this. As mentioned previously, this power will come out of the wall outlet and through a power adapter (AC to DC converter) that will produce the 24VDC input to the circuit breaker.

For the proposed breaker module, the mechanical project specifications consist of a manual, mechanical switch that will be used to actuate fault configurations set up by students taking the lab course. Mechanical buttons will be used to manually open and close the circuit breaker as well. These buttons are connected to relay inputs to allow the breaker to work.

The targeted dimensions of the proposed circuit breaker are shown in Figure 3.3. The circuit breaker is 9.5 inches long, 5.75 inches wide, and 3 inches tall. The volume of the circuit breaker is 163.875 cubic inches. These dimensions do not include any extruding parts such as the power cable or the top connection points.

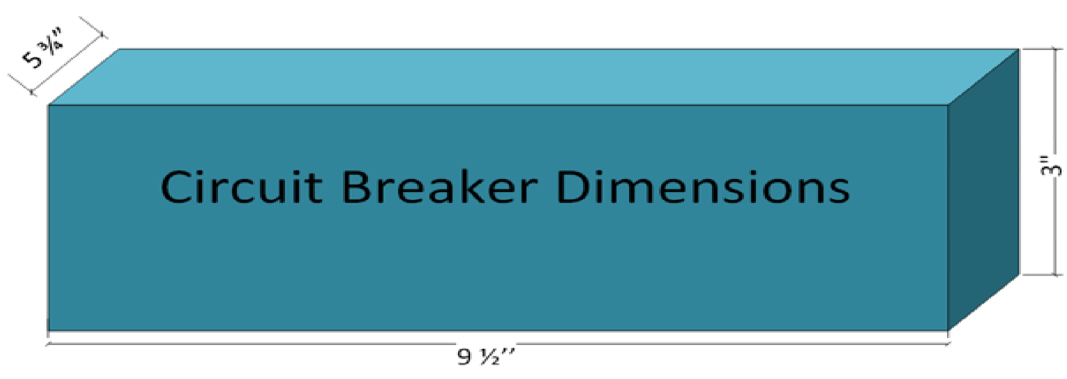

Figure 3.3: Circuit Breaker Dimensions

Table 3.1 summarizes all of the specifications that will be required for this senior project.

Table 3.1: Summary of Parameters

Parameter	Summary
Replace bench DC voltage with wall plug	• Use a wall outlet as the power source so that the breaker can be used anywhere where there is wall power. • 2 banana jacks will be removed from the faceplate since the bench will not be required for power • Requires an AC to DC converter • Will provide 24VDC to the circuit breaker • Reduces the number of wires that go to the bench
Remove connections between breaker outputs and fault inputs	• The 3 banana jacks on the "Fault" section of the box that are unnecessary • The connections will be made internally rather than with external short leads.
Build 12-15 more breakers	• 14 breakers are needed to allow 2 circuit breakers on each of the 7 lab benches • 1 extra breaker as a spare
Rearrange Faceplate	• A more intuitive faceplate configuration will allow users to understand what is going on more clearly
Lower cost per breaker	• The new breaker design uses 24VDC, allowing for cheaper components with reduced ratings • Lower costs will allow for the production of more circuit breakers in the future

4. Design

To begin the redesign of the circuit breaker, the previous circuit breaker was examined. Its bill of materials was reviewed in order to identify part numbers, names, costs, and vendors, and an existing circuit breaker was then deconstructed in order to draw a new circuit schematic. Using this new schematic, improvements were then brainstormed and proposed. The first improvement was rearranging and removing parts on the faceplate. Hole sizes for banana jack terminals, LEDs, and buttons were determined by referring to the AutoCAD files provided with the existing circuit breaker. For parts that were not included in the original AutoCAD files, sizes were determined by measuring the components in person when they arrived from the vendor or using specifications on component datasheets. For example, the new breakers will involve smaller LED's than the ones previously used, so the size of the holes on the faceplate will be reduced to allow the new LEDs to be mounted properly. Some component placements were shifted on the faceplate, such as the input and output banana jack terminals. The terminals for each of the three phases were changed to lay out vertically and connect linearly from the left side to the right side of the faceplate for more intuitive use, which reflects the design requirements mentioned in Chapter 3. Other banana jack terminals were removed from the faceplate altogether and connected internally to further improve ease of use. This was done by internally connecting the Circuit Breaker Output connections to the Input Fault connections, then to the switch and the Output Fault connections terminals. Once these improvements were finalized, a draft was hand-drawn and then copied over to AutoCAD. This AutoCAD file was sent to a contact who laser cut the faceplates out of a piece of acrylic, which will be discussed in Chapter 5. The new redesigned faceplate schematic is shown in Figure 4.1.

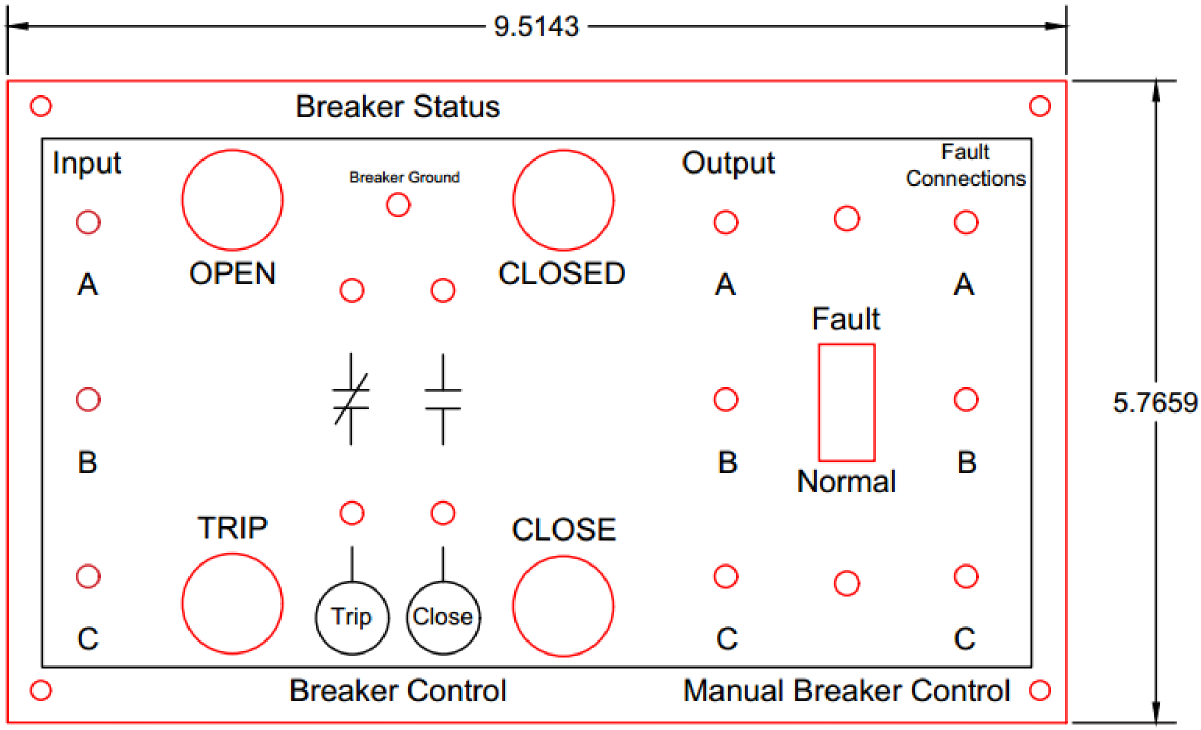

Figure 4.1: Dimensions of Redesigned Acrylic Faceplate. Red coloring indicates cut-through lines; black indicates surface etchings for text and symbols.

The next step in the design process was implementing an AC to DC converter to allow the circuit breaker to receive power from a common wall outlet instead of the DC connections on the Cal Poly test benches. A laptop charger was chosen to achieve 24 VDC from a 120VAC wall outlet. The charger is plugged into a jack on the side of the breaker which will serve as the main power connection to the inside of the breaker. Running off of 24 VDC rather than 125 VDC allowed the costs and rating sizes of several components to reduce significantly.

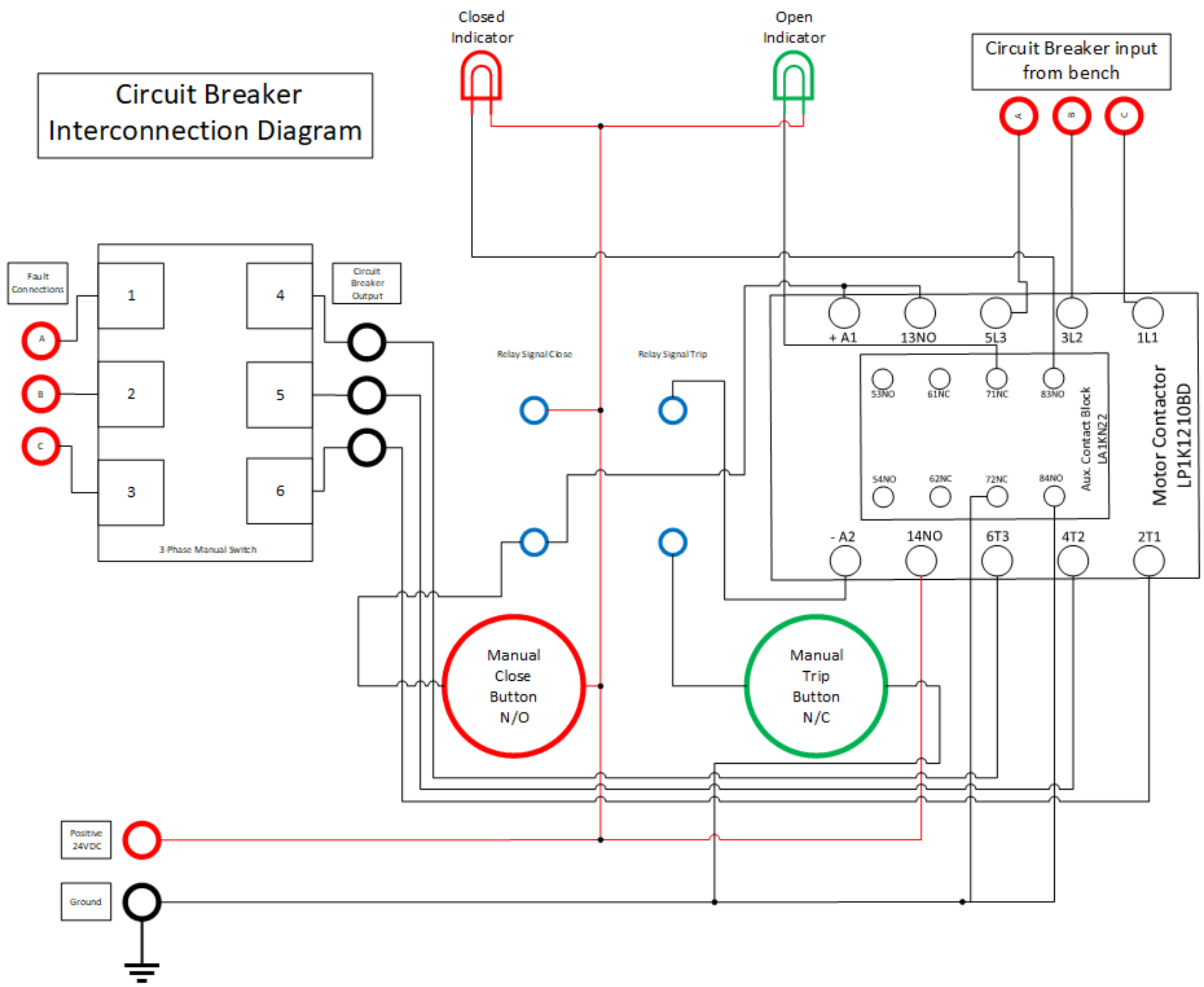

Figure 4.2: Interconnection diagram of internal hardware

The new circuit breaker design builds upon the previous circuit breaker design by directly improving issues it exhibited with layout, versatility, and cost. The new layout makes the circuit breaker connections more intuitive and logical for students, and its cost was decreased due to removing components and lowering several component ratings.

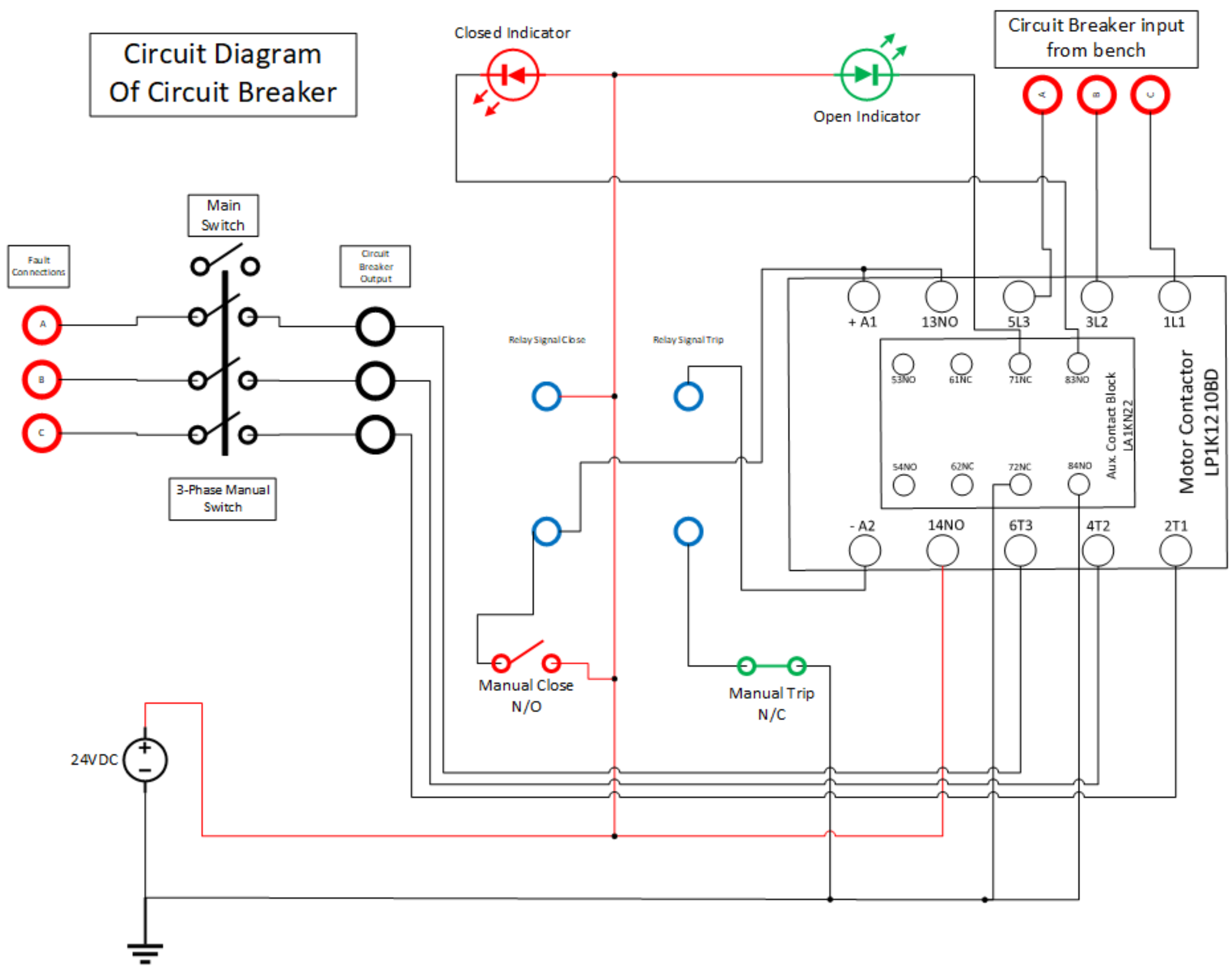

Figure 4.3: Circuit schematic using circuit elements. The motor contactor and auxiliary motor contactor contain a network of switches that are discussed later

Figure 4.3 shows the circuit schematic that will be used to make the internal connections when building the circuit breaker.

The use of the motor contactor is necessary to manage the number of switches needed for proper operation. The motor contactor itself contains a series of switches. The default position of the switches, normally open or normally closed, is stated on motor contactor datasheets. For example, the motor contactor being used in the circuit breaker is the LP1K1210BD. The model number dictates what is inside the motor contactor. Since this is a 3 Pole + N/O contactor, the N/O switch is what dictates the number that comes after LP. In this case, LP1K1210BD means that there is 1 normally open auxiliary contact. The next sequence of 3 characters, K12, indicates the characteristic of these poles. Information about these are in the datasheet. The second to last two characters, LP1K1210BD, indicates whether the contactor contains a normally open or normally closed auxiliary switch. The "10" indicates a normally open auxiliary switch, shown as the T4/8 - 7/L4 switch in Figure 4.4. In another case when this number reads "01", this indicates

that the auxiliary switch is normally closed. The last two characters, LP1K1210BD, indicate the operating coil. The suffix BD requires 24VDC, but a contactor ending in ED would require 48VDC. This voltage is delivered via +A1 and out -A2.

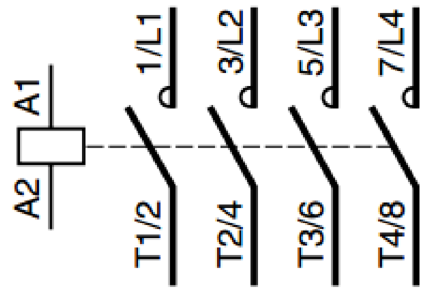

Figure 4.4 - Internal wiring of LP1K1210BD

A similar process is used to describe the auxiliary contactor. The purpose of the auxiliary contactor is to provide additional normally open and normally closed contact. For this design, we are using the LA1KN22 auxiliary contact block. This model number can also be broken down. The second character, A, indicates an auxiliary switch. The 22 indicates the number of normally open and normally closed poles. For our auxiliary switch, 22 indicates 2 normally open and 2 normally closed poles. Other auxiliary switches, like the LA1KN13, contain 1 normally open pole and 3 normally closed poles. The last character, M, is an optional “mounting” variant of the LA1KN22 auxiliary block. Figure 4.5 shows the 2 N/O and 2 N/C configuration of the LA1KN22 auxiliary block.

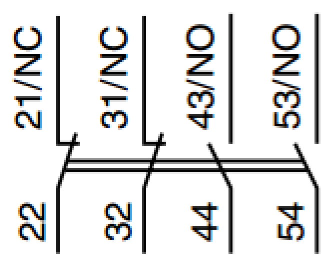

Figure 4.5 - Circuit Schematic of the LA1KN22M contact block.

5. Hardware Tests and Results

To build the circuit breakers, parts and must first be obtained. The Bill of Materials can be found in Appendix A. Once all of the materials are obtained, follow the circuit schematic, shown in Figure 4.2 in the previous chapter, and connect all the parts together. Suggestions on building procedure are as follows:

1. Screw in manual switch to the faceplate using screws and nuts.
2. Screw in open and close buttons and LEDs.
3. Screw in all banana jack terminals with nuts.
    a. Three red terminals should be used for the inputs, three black terminals should be used for the outputs and another three black terminals should be used for the fault connections.
    b. Four blue terminals should be used for the manual trip and close connections.
    c. Tighten all terminals with nut drivers to ensure maximum safety and security.
4. Attach the auxiliary contact block to the motor contactor and place on the faceplate on their sides so the labels face up.
5. Cut wires of lengths based on how far the connection that must be made is.
    a. 12 AWG wires must be used for anything connected to the inputs, outputs and fault connections.
    b. 16 AWG wires will be used for all other connections.
6. Strip the ends of each wire.
7. Crimp the end of each wire that must be connected to a banana jack terminal with a ring terminal.
    a. These rings can then be slid on top of the appropriate terminal and screwed in place with a nut. A nutdriver is suggested for this step to make sure that the nut is tight enough.
8. Unscrew the screws on the switch, buttons, LEDs, auxiliary contact block, and contactor.
9. Insert a stripped wire (without a ring terminal) under the appropriate screw terminal then tighten down using a phillips head screwdriver.
10. For the power connections, stripped wires without ring terminals will need to be soldered to the DC Barrel Power Jack.
    a. Be sure to check which is the positive terminal and which is the negative terminal before soldering.
11. The ground terminal and DC Barrel Power Jack will need to be attached to the side of the chassis.
12. The final step is to carefully place the faceplate with all of the parts attached to it right side up on the chassis and screw it in.

Figure 5.1: Top View of Final Circuit Breaker

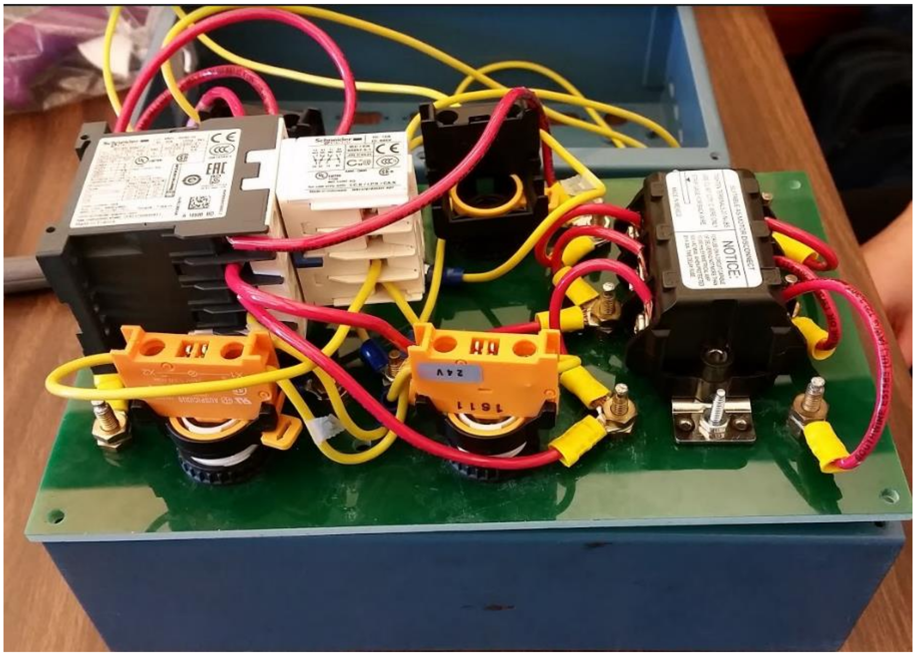
Figure 5.2: Internal View of Final Circuit Breaker

Single Line to Ground Fault

A single line to ground fault is created by attaching a banana-banana lead from a phase fault terminal to the green chassis ground terminal. This will simulate a single line to ground fault. Figure 5.3 shows a single-line-to-ground fault configuration and shows that there is about 0 ohms across the lines.

Figure 5.3 Top view of Single-Line-to-Ground Fault Configuration

Double Line to Ground Fault

A double line to ground fault is created by shorting two phases together and then connecting one phase to the green chassis ground terminal. This can be seen in Figure 5.4. Once again, there is about 0 ohms across the lines.

Figure 5.4 Top view of the Double-Line-to-Ground Configuration

Line to Line Fault

A line to line fault is created by shorting two phases together. This is to simulate wires making contact with each other, all the while not contacting the ground. Figure 5.5 shows the line-to-line fault configuration and that there is about 0 ohms across the lines.

Figure 5.5 Top View of Final Circuit Breaker with a Line-to-Line Fault Configuration

Three Phase Fault

The three phase to ground fault is created by shorting all of the phases together. This is to simulate all three wires making contact with each other but not contacting the ground. Figure 5.6 shows this connection and once again, there is about 0 ohms across the lines.

Figure 5.6 Top View of the Three-Phase Fault Configuration

To test the circuit breaker's functionality a few steps need to be taken. The first check is

to use a multimeter to check continuity and voltage drops across each device. Next, the LEDs and buttons must be tested by shorting the trip terminals using a short banana-to-banana lead. A banana-to-banana lead will also need to be used to ground the chassis. Insert the AC to DC converter into a plug socket and check to see if the green LED turns on. Assuming it turns on, manually press the red close button. This should result in the green LED turning off and the red LED turning on. Then press the green button to turn off the red LED and turn on the green LED. To test this functionality under high stress conditions, quickly alternate between pressing the two buttons. Figure 5.7 shows the circuit breaker with the green LED on, as the trip button was being tested. Here, a line-to-line fault was set up and the circuit breaker was closed. Then when the fault switch was switched as seen in the picture, the circuit breaker opened and the green LED turned on.

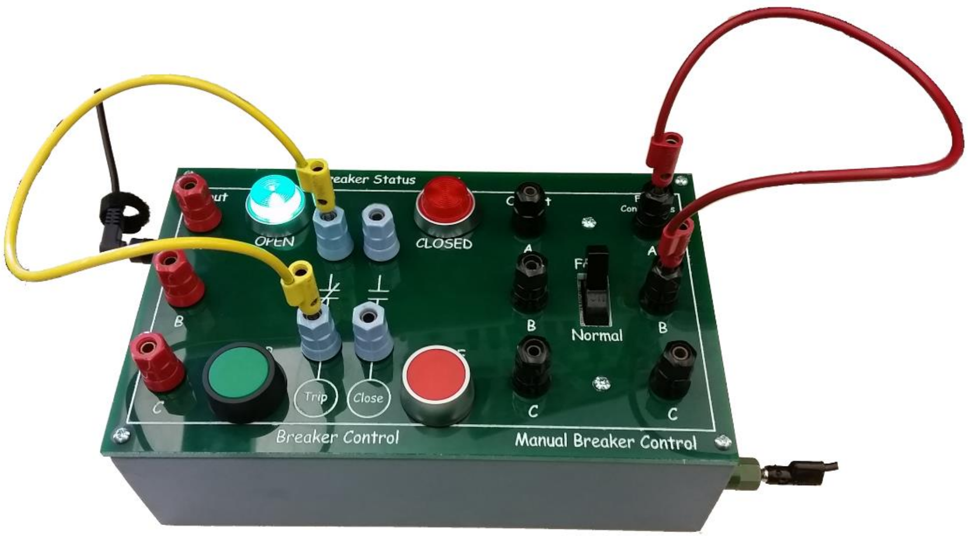

Figure 5.7: Top View of Final Circuit Breaker after a Line-to-Line Fault has occurred

The final test is to put the circuit breaker into a simple circuit in the power lab. This test will be checking to make sure that the fault switch and fault configurations work as designed. This testing of the circuit breaker involves the use of a 710 Relay, and induction motor, and a Variac autotransformer. This procedure is derived from the EE 444 Experiment 5: SEL-710 Motor Relay lab written by Kenan Pretzer [9]. Completion of this procedure will test a line-line fault and a 3 phase fault. Successful completion of this procedure will test all aspects of the circuit breaker's designed operation setting.

<u>List of Materials</u>

- 25-Ω Single-Phase Power Resistor (3x)
- Bag of Banana-Banana Short Leads (3x) *
- 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

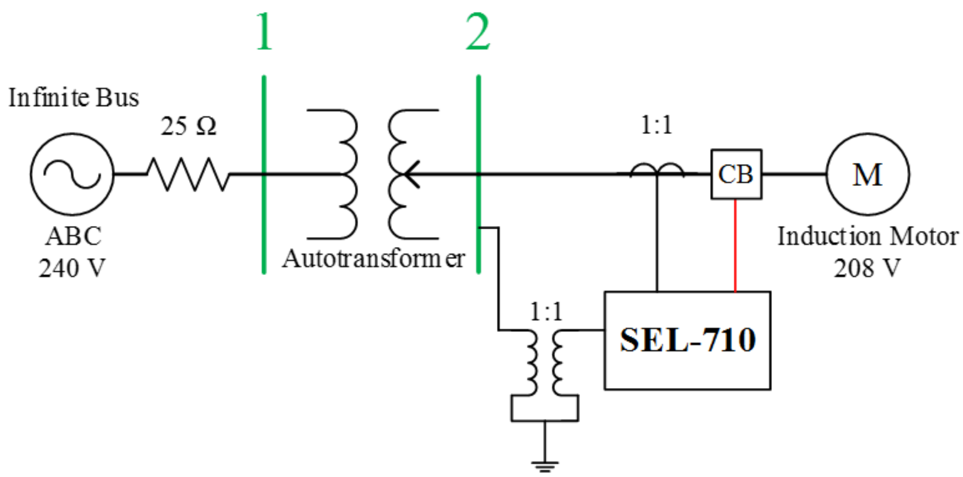

Figure 5.8 Radial Resistive Circuit Single-Line Diagram

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.

   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 under voltage 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 under voltage condition, increase the value of the under voltage 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 under voltage 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 under voltage 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 under voltage 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 under voltage 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 under voltage 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 5.5, 5.6, and 5.7.

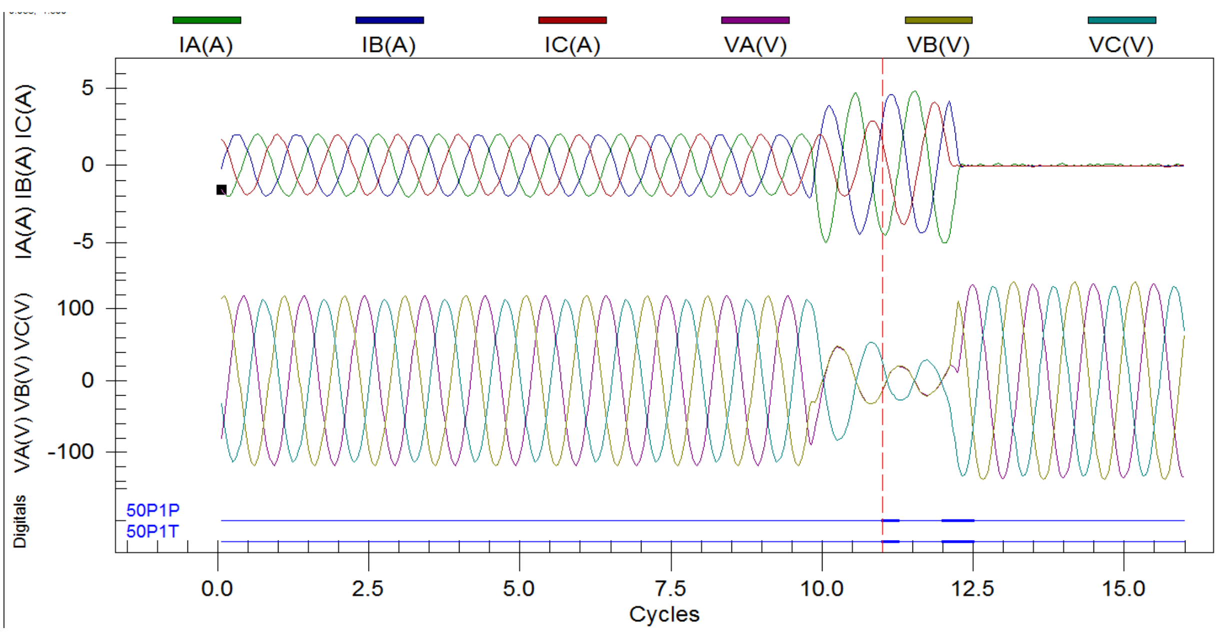

Figure 5.9 Line-to-Line Fault Oscillogram Plot.
From the graph, one can see the normal operating currents followed by the sudden increase in current. One can derive from the graph the time it takes for the relay to operate in an overcurrent condition.

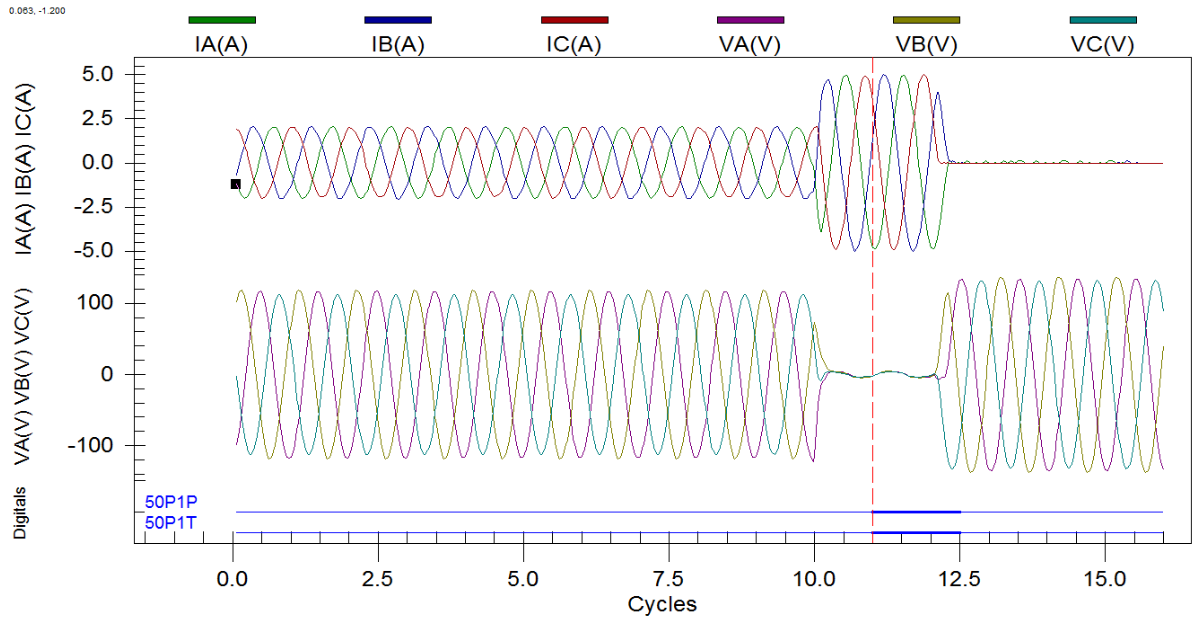

Figure 5.10 Three-Phase Fault Oscillogram Plot.
Similar to the line to line fault in figure 5.5, the 3 phase fault shows an increased current when the fault occurs. The 710 relay took approximately 1 cycle to operate.

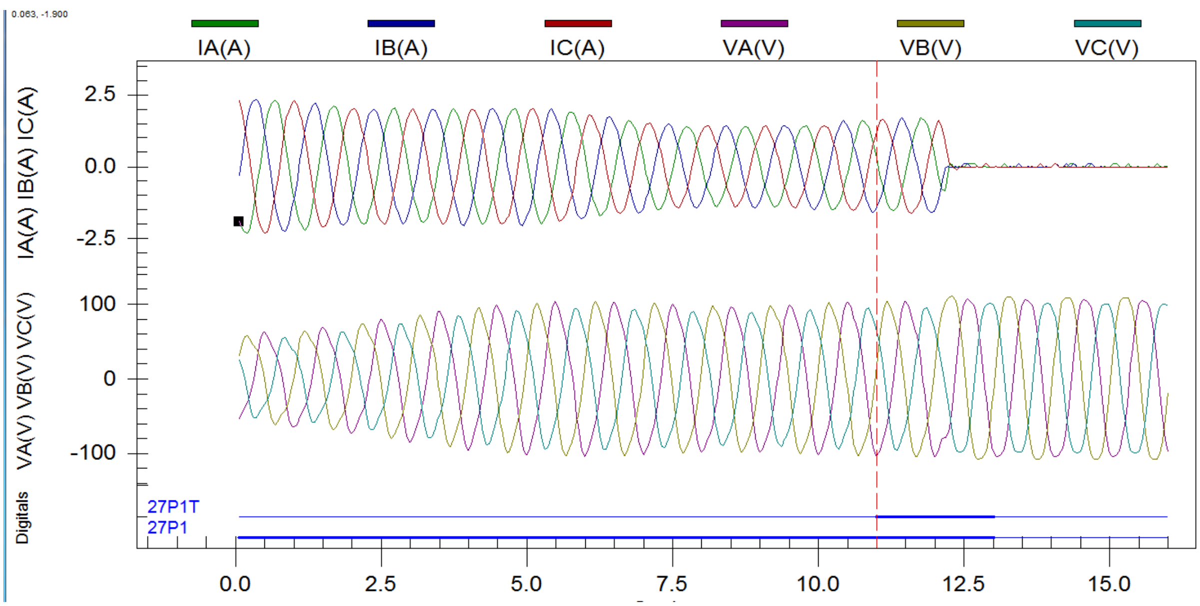

Figure 5.11: Under voltage Condition Oscillogram Plot.
The graph shows the slow decrease in voltage across the motor terminals until the undercurrent relay begins to operate. The top oscillogram shows that it takes approximately 1.5 cycles to operate.

Once these tests have been completed the circuit breaker functionality has been confirmed. If one test does not pass the test, troubleshooting must occur. To troubleshoot, check to make sure the relay settings are correct. If all relay settings are correct, then check the wiring

configuration. If all connections are correct, use a multimeter to check for continuity and correct voltage drops across devices.

6. Conclusion

In this project, a circuit breaker box that can simulate different type of power system faults was designed, constructed, and then tested. The project also aims to improve the circuit breaker box from the previous design by simplifying the connection setup and thus reducing the number of wires required to simulate the faults. Hardware testing of the improved circuit breaker box demonstrates its full functionality. The subsequent paragraphs describe additional improvements of the breaker box which will further provide simpler and safer operation when used in conjunction with a fault test circuit.

First, to obtain better results, a larger chassis could be used. This would allow for more space to wire the circuit breaker as well as allow for different spacing of the components on the acrylic faceplate. The current chassis being used is fairly small, has only one spot to put the ground terminal, and one place to put the power terminal in the side. The holes that were already drilled into the chassis were bigger than the power and ground terminals, resulting in problems when attaching the parts. With a chassis made specifically for the circuit breaker, holes can be drilled that match the size of the power and ground terminals, and in the correct place for the most logical setup possible. This would also make any future development without the chassis a challenge since the faceplate design also relies on the size of the chassis.

Another improvement that could be made is allowing more space between the switch and the output terminals. Due to the fact that the output terminals are hot, there is some danger when switching the switch as the person’s hand could accidentally touch the terminals and hurt themselves. To make operating the fault switch easier, the circuit breaker could be larger to allow for more space. Another option would be to offset the terminals from the switch so that the switch is closer to the bottom of the faceplate where hands will be and the terminals will be at the top of the faceplate. Due to space restraints on the current circuit breaker, this problem would be hard to fix but with a larger breaker, this would be an easy improvement to make and allow for safer use.

One final improvement could be parts availability. A number of the parts are somewhat hard to find. It would be preferable if possible to find an alternative manufacturer for each of these parts. It would also make the logistic better if all the parts can be obtained from one vendor, but the range of parts needed for the box is very wide, and so this may not be feasible. For example, the buttons will most likely not be available from the same place as the power connector or motor contactor.

To help students fully understand how real world utility power systems are affected by faults, circuit breakers have been made and improved for a power systems lab. These circuit breakers have been improved from a past project and built with less expensive, lower rated parts. This means the circuit breaker is safer and easier to reproduce. The circuit breaker is more linearly laid out so that the students can gain more insights from the labs and aren’t spending the entire lab trying to figure out what the circuit breaker is doing and how it is connected. Documentation has been made to better reproduce the circuit breakers and make as many as are

needed in any future power systems, microgrid, or protection lab. The circuit breaker can also be reproduced in other schools as they are powered using a computer charger and can be plugged into any wall outlet. As long as the school has protective relays, the circuit breakers can be used to help simulate a real world power system.

While the circuit breakers could still be improved further, they will be able to help many students in the future whether from Cal Poly or from another school that wants to use the design. They could also help utilities teach new employees what is happening in a fairly straightforward way as well.

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Appendix A - Bill of Materials

Description	Part No.	Quantity	Price Per Unit	Total Cost	Vendor
Green Button	PBF-22G	1	$7.95	$7.95	eBay
Red Button	PBF-22R	1	$7.95	$7.95	eBay
Motor Contactor	LP1K1210BD	1	$40.45	$40.45	Amazon
Red LED	PLN-22A Red	1	$5.95	$5.95	eBay
Green LED	PLN-22A Green	1	$5.95	$5.95	eBay
Auxiliary Contact Block	LA1KN22	1	$14.20	$14.20	Schneider Electric
24VDC Laptop Charger		1	$11.39	$11.39	eBay
DC Barrel Power Jack/Connector	CP-002A-ND	1	$0.60	$0.60	Digi-key
3-Phase Manual Switch	30003D	1	$50.00	$50.00	Automation Direct
Red Banana Jacks	501-1080-ND	3	$1.85	$5.55	Digi-key
Black Banana Jacks	501-1078-ND	6	$1.85	$11.10	Digi-key
Blue Banana Jacks	501-1084-ND	4	$1.85	$7.40	Digi-key
Green Banana Jacks	501-1083-ND	1	$1.85	$1.85	Digi-key
12 AWG Wire	55671523	1	$23.13	$23.13	Amazon
16 AWG Wire	55668023	1	$12.44	$12.44	Amazon
Acrylic Faceplate	N/A	1	$20	$20	Cal Poly
Chassis	N/A	1	Donated	Donated	Cal Poly
12 AWG Ring	N/A	10	$0.38	$3.80	Amazon

Terminals					
16 AWG Ring Terminals	N/A	20	$0.19	$3.80	Amazon
Crimping Tool	VDV226021SEN	1	$29.97	$29.97	Amazon
Wire Strippers	48-22-6109	1	$17.97	$17.97	Home Depot
Soldering Setup	N/A	1	$30	$30.00	Amazon
Phillips Head Screwdriver	N/A	1	$1.49	$1.49	Home Depot
Flat Head Screwdriver	N/A	1	$1.90	$1.90	Home Depot
Nuts	M5-.80	30	$0.35	$10.50	Ace Hardware
Screws	N/A	6	$1.25	$7.50	Home Depot

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**”)

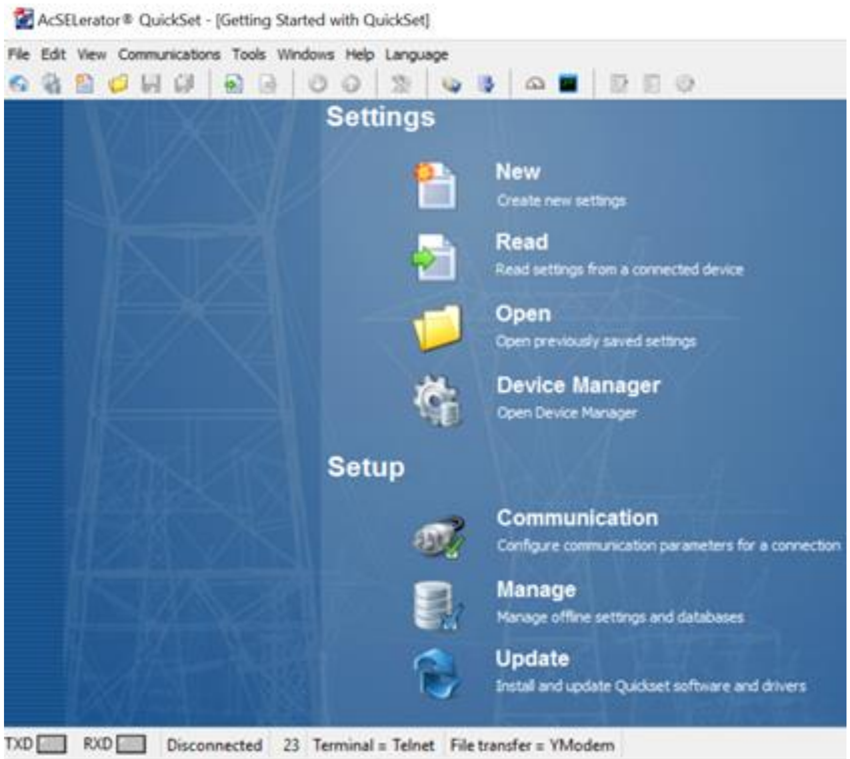


Figure B1: QuickSet Main Window

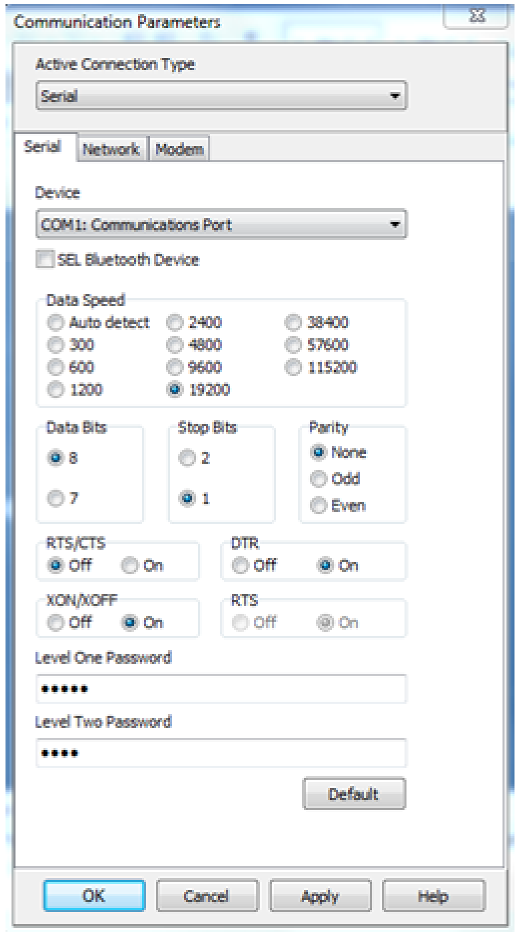


Figure B2: SEL-710 Communication Parameters Window

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.

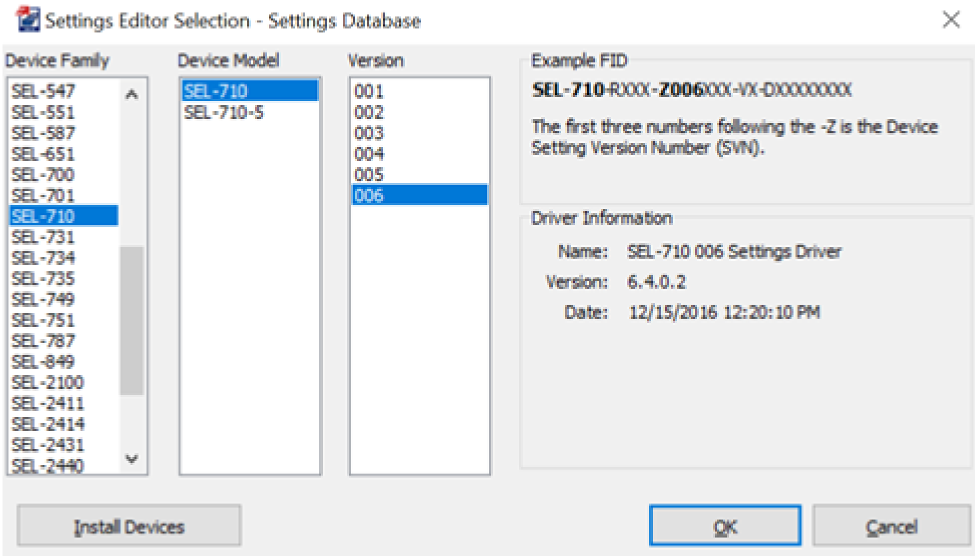


Figure B3: Identifying SEL-710 Relay Family, Model, and Version

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.

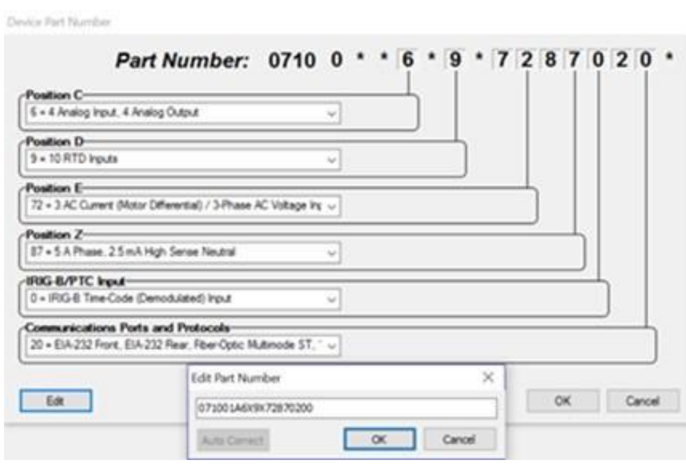


Figure B4: Identifying SEL-710 Relay Part Number

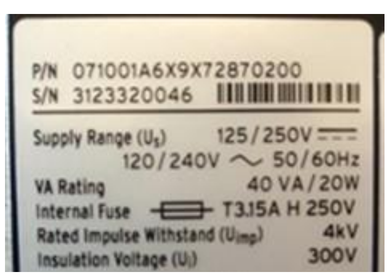


Figure B5: Example SEL-710

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.

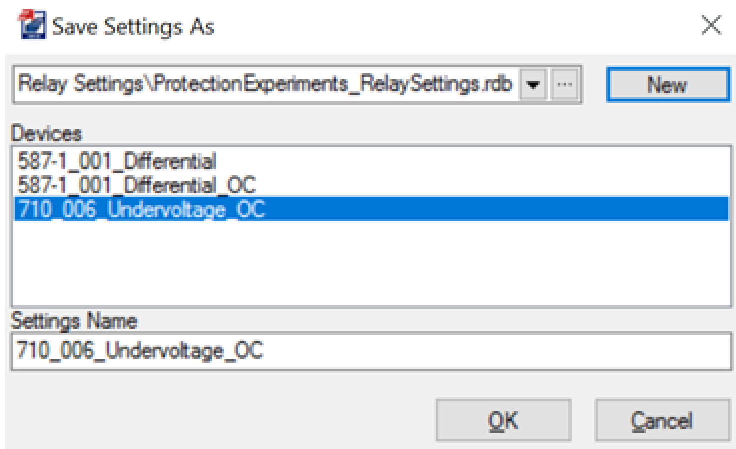


Figure B6: Saving SEL-710 Settings

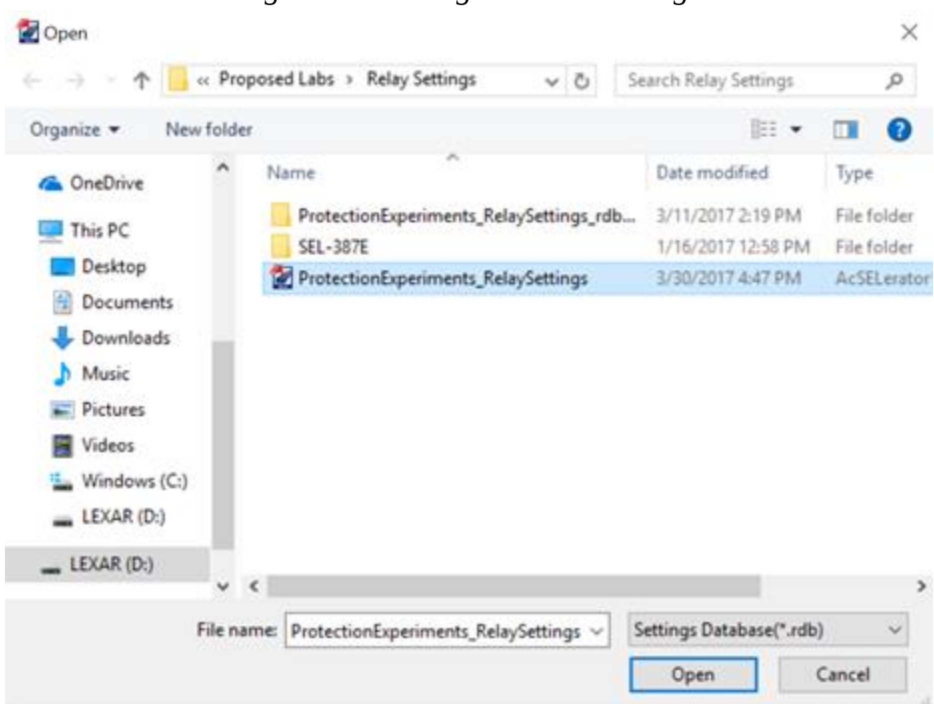


Figure B7: Choosing Location for New SEL-710 Relay Settings Database

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.

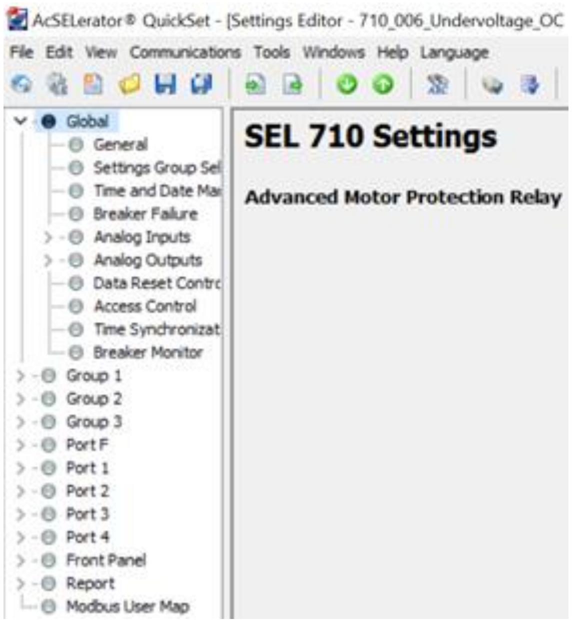


Figure B8: SEL-710 Settings Editor Main Window

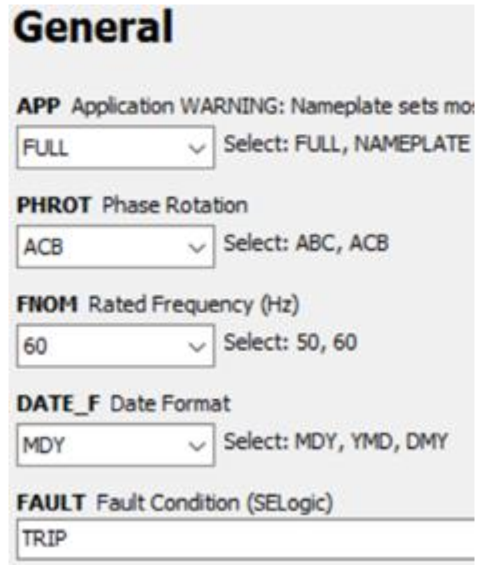


Figure B9: SEL-710 General Settings

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 of 1.6 A. 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.

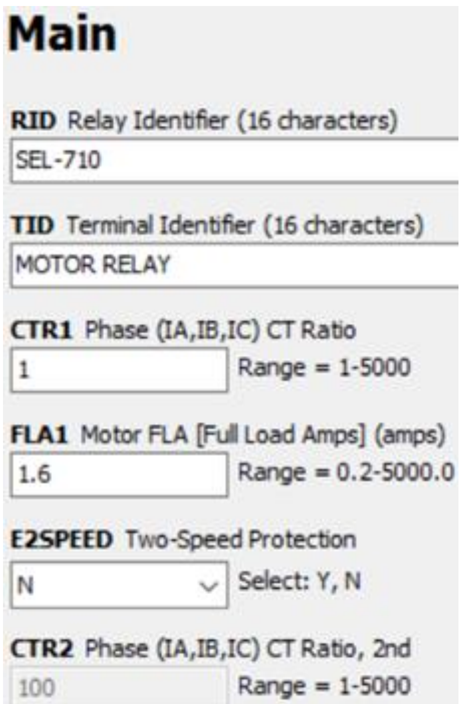


Figure B11: SEL-710 Main Settings

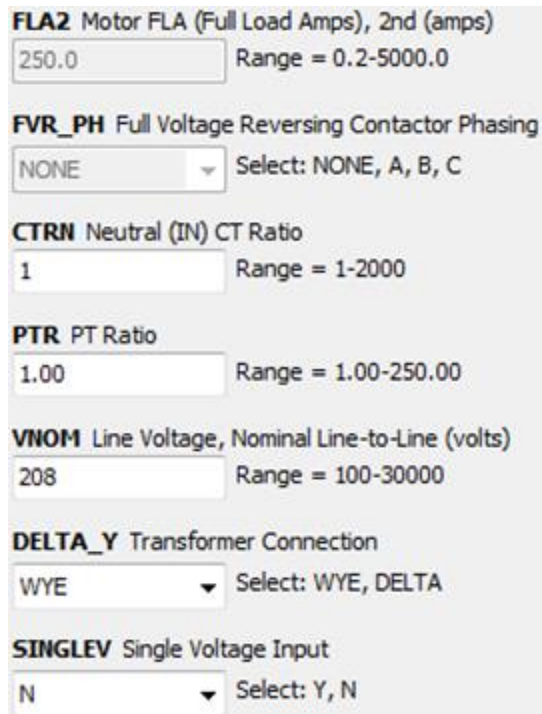


Figure B12: SEL-710 Main Settings, cont.

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**).

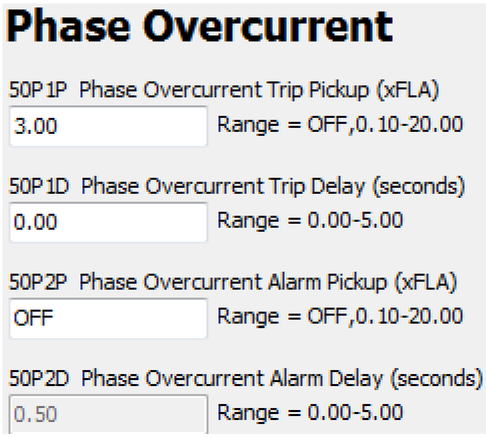


Figure B13: SEL-710 Phase Overcurrent Settings

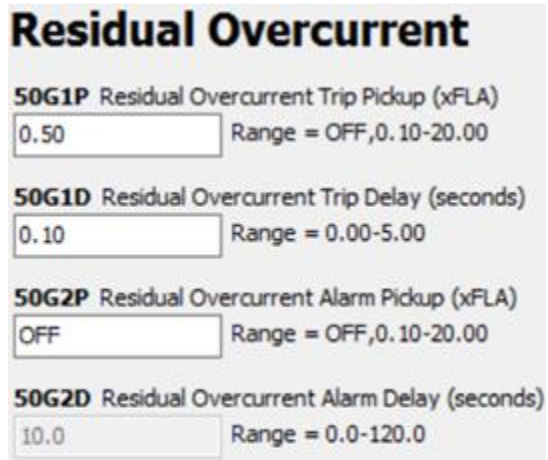


Figure B14: SEL-710 Residual Overcurrent Settings

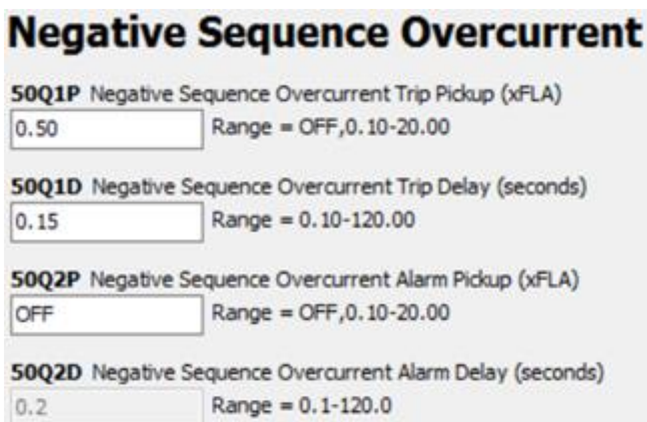


Figure B15: SEL-710 Negative-Sequence Overcurrent Settings

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

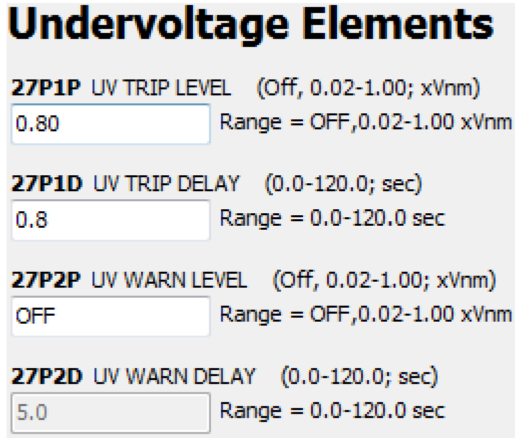


Figure B16: SEL-710 under voltage Elements

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).

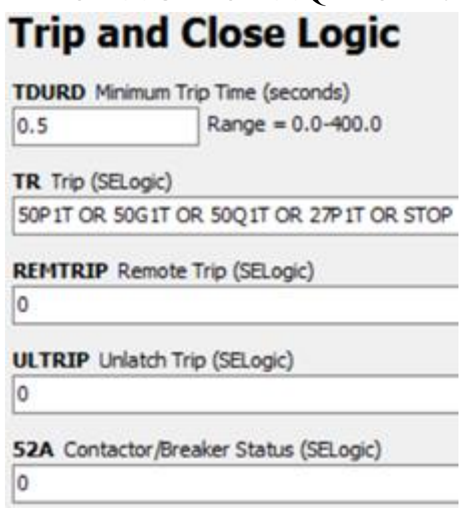


Figure B17: SEL-710 Trip and Close Logic

15. Enter the following information in the Logic 1, Slot A section (Figure B18).
    A. Select "N" for the OUT101 Fail-Safe (**OUT101FS**) option.
    B. Select "Y" for the OUT102 Fail-Safe (**OUT102FS**) option.
    C. 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.

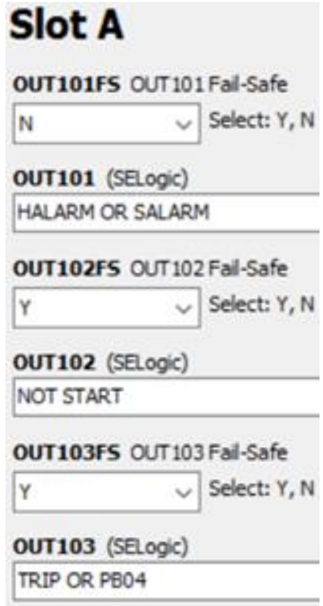


Figure B18: SEL-710 Logic 1, Slot A Output Logic

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).

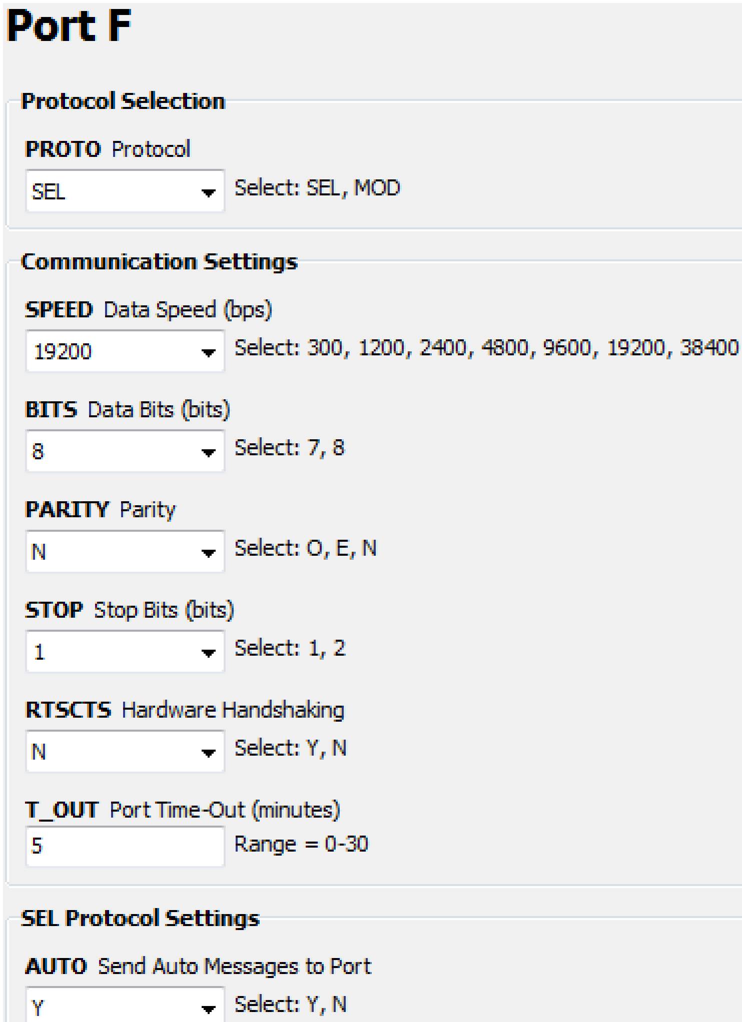


Figure B19: SEL-710 Port F Settings

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.

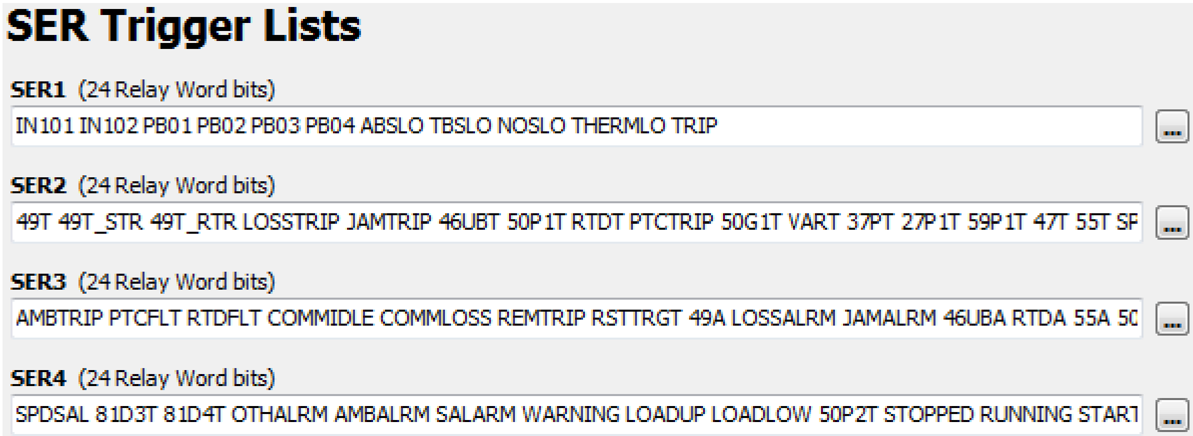


Figure B20: SEL-710 Trigger Lists Settings

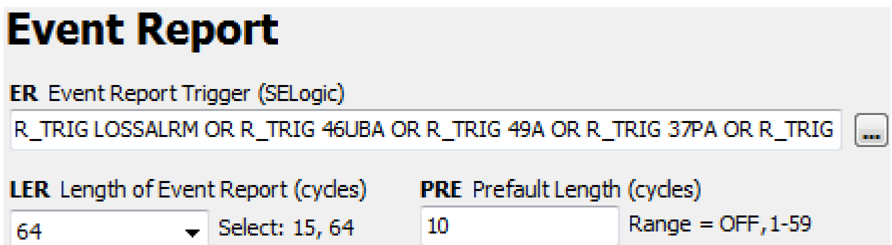


Figure B21: SEL-710 Event Report Settings

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.

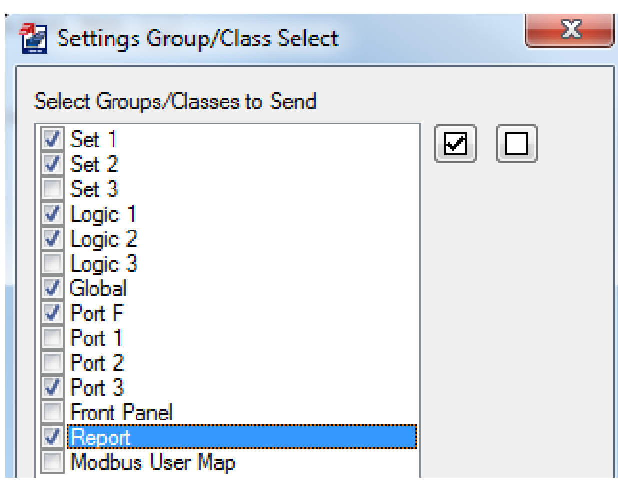


Figure B22: Send Modified Settings to the SEL-710

Appendix C - Analysis of Senior Project Design

Project Title: Lab-Scale Circuit Breaker Module For Power System Laboratories
Student's Name: Amanda Barley, Josh Chung, Allen Scozzari

Advisor's Name: NFN Taufik
Date: 6/12/17

Summary of Functional Requirements

- **Describe the overall capabilities or functions of your project or design. Describe what your project does. (Do not describe how you designed it).**
    - A lab-scale circuit breaker was designed for future Cal Poly power protection laboratory courses. The circuit breaker allows students to create faults in a lab setting that simulates a power system. The circuit breaker can also interface with SEL relays to analyze how faults affect current, voltage and other aspects in the system. These circuit breakers are redesigned models of a circuit breaker that was built for a previous student's senior project. The new model has an improved faceplate layout, it is powered using a standard AC wall plug and adapter that converts 120VAC to 24VDC, and has reduced costs.

Primary Constraints

- **Describe significant challenges or difficulties associated with your project or implementation. For example, what were limiting factors, or other issues that impacted your approach? What made your project difficult? What parameters or specifications limited your options or directed your approach?**
    - The difficulties encountered mainly included finding the necessary parts. Some of the parts are not commonly used and harder to find, especially for a cheap cost. However, the previous circuit breaker was available for reference for the type of parts needed. Although the new parts are of the same type but with reduced voltage rating, there was a limitation due to finding these parts at specific voltage and current ratings. Additionally, some components, such as the metal chassis and banana jack terminals, were used because they were donated by Cal Poly and other sources that are unknown. Since these specific parts cannot be purchased, they are a limiting factor in the manufacture of future circuit breakers.
    - Space constraints were another factor that existed due to the metal chassis available. To reduce costs, the same type of metal chassis used in the previous design is used in the new design. This limited the size of the acrylic faceplate and the possible new layouts that could be implemented for the faceplate design. The size of the chassis also requires that the internal wires and components must be carefully arranged to be able to fit into the chassis, which increases the time it

takes to build each circuit breaker.

Economic

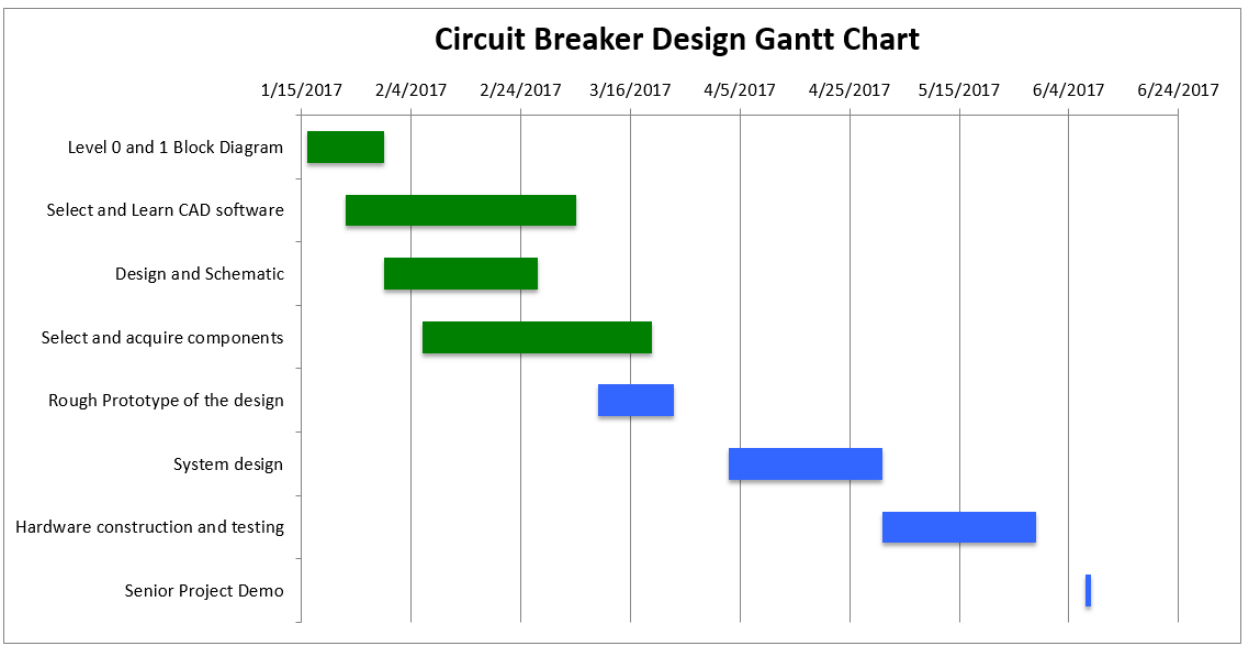
- **What economic impacts result? Consider:**
  - **Human Capital – What people do.**
  - One person can build one circuit breaker in approximately 4 hours.
  - **Financial Capital – Monetary instruments.**
  - The new circuit breaker cost is approximately $150, down from the original $300. This saves money for Cal Poly or other parties making the new circuit breaker.
  - **Manufactured or Real Capital – Made by people and their tools.**
  - The motor contactor, auxiliary motor contactor, and fault switches are likely less commonly purchased items. The circuit breakers can increase demand for these items.
  - **Natural Capital – The Earth's resources and bio-capacity.**
  - Most parts are made of metal such as silicon and iron that have production cycles that can harm the environment.

- **When and where do costs and benefits accrue throughout the project's lifecycle?**
  - Costs of the project accrue at the beginning when obtaining the parts for the product and the tools to build the product. Each circuit breaker requires approximately four hours to build, which is time that may be compensated for, at a cost to the employer or organization. Benefits are accrued at the end of the project lifecycle when the product is built and implemented in a lab setting for student use.

- **What inputs does the experiment require? How much does the project cost? Who pays?**
  - The inputs the experiment requires include the parts for the circuit breaker, tools used to build it, and people to construct it. The Cal Poly EE department pays for the project through reimbursements of up to $200 for each student working on the project.
  - **Original estimated cost of component parts (as of the start of your project).**
  - The original estimated cost of the components was about $200 per circuit breaker module.
  - **Actual final cost of component parts (at the end of your project)**
  - The final cost of the components was about $150 per circuit breaker module.
  - **Attach a final bill of materials for all components.**
  - A bill of materials can be found in Appendix A of the project report.
  - **Additional equipment costs (any equipment needed for development?)**
  - Tools needed for development can also be found in the bill of materials in Appendix B of the project report.

- **How much does the project earn? Who profits?**
    - The project does not make any money, as it is a tool used by students to learn and gain knowledge about power systems and faults.

- **Timing**
    - **When do products emerge? How long do products exist? What maintenance or operation costs exist?**
    - The products will start being used in the Spring Quarter of 2018 when EE 444 class is offered. They will exist as long as the product functions as intended and the lab course is offered.
    - Maintenance will only be done on an as needed basis if a circuit breaker stops working as it should. This shouldn't happen very often as they were made to be fairly sturdy to withstand the use by students.
    - **Original estimated development time (as of the start of your project), as Gantt or Pert chart Actual development time (at the end of your project), as Gantt or Pert chart**
    - The development time can be found in the Gantt chart below:



    - **What happens after the project ends?**
    - After the project ends, students will be able to use the circuit breakers and if so desired, more breakers can be produced.

If manufactured on a commercial basis:

- **Estimated number of devices sold per year**

    - These devices will not be sold and will be used for Cal Poly only for the time being
- **Estimated manufacturing cost for each device**
    - The manufacturing cost for each device is approximately $150 per breaker.
- **Estimated purchase price for each device**
    - Since the breakers will not be sold, there is no purchasing price.
- **Estimated profit per year**
    - The circuit breakers will not be sold and gain no profit.
- **Estimated cost for user to operate device, per unit time (specify time interval)**
    - There is no cost for the user to operate the device. The cost of electricity used is paid for by Cal Poly.

Environmental

- **Describe any environmental impacts associated with manufacturing or use, explain where they occur and quantify.**
    - The circuit breakers do not directly have an environmental impacts associated with manufacturing, except for shipping the parts to the location where the circuit breaker will be built.
    - Making the parts could cause environmental impacts but those are very slight due to the small number of breakers being produced.
    - Using the circuit breaker will impact the environment only very slightly due to the use of electricity to power the breaker.
- **Which natural resources and ecosystem services does the project use directly and indirectly?**
    - The project uses electricity from PG&E directly.
- **Which natural resources and ecosystem services does the project improve or harm?**
    - The project does not improve natural resources or ecosystem services and does very little to harm them.
- **How does the project impact other species?**
    - The project doesn't impact other species.

Manufacturability

- **Describe any issues or challenges associated with manufacturing**
    - Obtaining the parts can be challenging and making sure that all the internal connections are made correctly can cause problems. Following the schematics in the report will allow manufacturers to make sure that all wiring is done properly.

Sustainability

- **Describe any issues or challenges associated with maintaining the completed device, or system.**
    - To maintain the completed device, there could be issues if a part stops working. In this situation, a new part must be found and ordered and replaced internally.
    - All connections internally are made either using ring terminals or screws that are

mounted onto some of the parts when they are first made. This makes replacing the parts very easy.

- **Describe how the project impacts the sustainable use of resources.**
  - This project does not use any materials from a known sustainable source. Acrylic, plastic, brass, copper wire, and all other parts do not have a defined sustainable source to begin with.
- **Describe any upgrades that would improve the design of the project.**
  - To improve the design, new chassis' could be used that are bigger allowing more space for the parts internally and externally.
  - The switch on the circuit breaker could also be moved farther away from the output terminals to prevent safety hazards.
- **Describe any issues or challenges associated with upgrading the design.**
  - Challenges associated with getting a bigger chassis include finding one or making a new one. If it is unknown how to make a chassis out of metal, then this could be difficult.
  - Challenges with moving the switch farther away from the output terminals include needing a larger chassis and breaker to make the room to move the switch.

Ethical

- **Describe ethical implications relating to the design, manufacture, use, or misuse of the project.**
  - As this project is meant to be used by students, they could use their newfound knowledge to cause problems in utility systems, but that is unlikely to happen because they would simply be causing faults in the system which utilities know how to deal with already.

Health and Safety

- **Describe any health and safety concerns associated with design, manufacture or use of the project.**
  - One safety concern is the switch being so close to the output terminals and a student accidentally touching the hot terminals when they go to switch the switch thereby injuring themselves greatly. Since this is a power systems lab, high voltage will be used running through the circuit and this could be a safety hazard.

Social and Political

- **Describe social and political issues associated with design, manufacture, and use.**
  - The social and political issues associated with this project are the electricity being used and the teaching of how to work a system in a utility.
- **Who does the project impact? Who are the direct and indirect stakeholders?**
  - The project impacts the students of Cal Poly. The direct stakeholders would be the Electrical Engineering department since they are the party responsible for seeing that they are used appropriately and correctly.

- **How does the project benefit or harm various stakeholders?**
    - The project benefits the stakeholders because it allows the Electrical Engineering department adequate lab materials for effective teaching.
- **To what extent do stakeholders benefit equally? Pay equally? Does the project create any inequities?**
    - The project could potentially create inequities if not enough new circuit breakers are built for all students to use them. If only some new circuit breakers exist, then some students will use the old model, which could lead to different laboratory experiences.
- **Consider various stakeholders' locations, communities, access to resources, economic power, knowledge, skills, and political power.**
    - The Cal Poly EE department will have more access to the circuit breakers than students, since they will likely be stored in room 102 of the Engineering East building. They also hold the most political power in being able to decide whether or not the circuit breakers will be used.
    - The future students using the circuit breakers will have some access to resources and political power. They will have access to the circuit breakers if professors allow them to use them during lab, and their feedback will determine if professors will continue to use the new circuit breakers. However, they will be the least familiar with the circuit breakers.

Development

- **Describe any new tools or techniques, used for either development or analysis that you learned independently during the course of your project. Include a literature search.**
    - AutoCAD software was learned independently in order to design the faceplates and allow them to be cut with the appropriate laser cutter.
    - The Titan Tools 11477 Ratcheting Wire Terminal Crimper was purchased for crimping, although learning to use it was simple