Motor Protection Lab Experiment using SEL-710

by

Ozro Corulli

Senior Project

ELECTRICAL ENGINEERING DEPARTMENT

California Polytechnic State University

San Luis Obispo

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Abstract

Advancements in microprocessor based relay technology for power protection applications provide quicker response times and new methods of mitigation. This project develops a lab experiment for Cal Poly class EE444 - Power Systems Laboratory based on the Schweitzer SEL-710 motor protection relay. Learning objectives for this lab include relay setup, programming, and protection schemes for the following conditions: undervoltage, loss of phase, fault, locked rotor, and thermal overload. Today, utility companies across the globe use SEL relays for primary system protection, putting engineers familiar with their operation in high demand.

Acknowledgments

There are a number of people and companies that made this project possible including the Cal Poly Electrical Engineering department, Schneider Electric, and Schweitzer Engineering Laboratories. Thank you to Cal Poly Electrical Engineering staff members Jaime Carmo and Corey Ricketts for their help in building the breaker and fault boxes. Thank you to Schweitzer Engineering Laboratories for their donation of SEL equipment, allowing us to gain hands on experience with equipment and practices currently being used in the industry. Thank you to Brett Roberts and Schneider Electric for their donation of motor contactors and switches, enabling us to create effective lab experiments. Thank you to the Cal Poly Electrical Engineering department for the financial assistance provided by the senior project fund, having financial support available to students helps tremendously in producing a quality project. Thank you to my faculty advisor and power professor Dr. Ali Shaban for his help and support not only in this project, but throughout my entire stay here at Cal Poly. It is because of professors like him that Cal Poly has the great reputation they hold today. Thank you to Don Heye for his generous financial support allowing me to focus on my schooling, and finally a big thank you to my wife, parents, family, and friends for their continuing help and support, I am truly blessed.

Chapter 1: Introduction

In January 2013, Schweitzer Engineering Laboratories donated over $160,000 in equipment to the Cal Poly Electrical Engineering Department. The donation outfitted Cal Poly's Power System Lab with state of the art power protection relays and testing equipment. Ed. Schweitzer, CEO and founder of Schweitzer Engineering Laboratories (SEL), revolutionized the utility industry in 1982 when he developed a microprocessor based relay capable of storing event data for further analysis. Today, utility companies across the globe use SEL relays for primary system protection, putting engineers familiar with their operation in high demand.

This project develops a laboratory experiment based on the SEL-710 motor protection relay for use in Cal Poly class EE444 - Power Systems Laboratory. The project follows standard Cal Poly lab methodology [10] and includes background, pre-lab, procedure, and follow-up question sections.

Topics for this lab include:

- Relay setup
- Relay programming
- Developing protection schemes for:
    - Under-voltage
    - Loss of phase
    - Line-to-line fault
    - Locked rotor
    - Thermal overload

Industrial size electric motors can cost millions of dollars, making their protection a high priority. The protection schemes explored in this lab combat: running the motor at less than rated voltage, the loss of a phase for 3-Φ motors, faults in the supply power, applying a load greater then recommended causing the motor to stall in a locked rotor condition, and overheating from excessive starting or running the motor above rated values. Information on implementing lab topics can be found in [3], [5], [6], and [8].

Chapter 2: Background

Depending on the size and importance of the motor, protection may be implemented in various ways ranging from a single-trip overcurrent breaker to a microprocessor controlled breaker with current and voltage monitoring. The SEL-710 is a microprocessor controlled protection relay that reads the voltage and current levels of the lines feeding the motor allowing it to monitor the motor's condition. The SEL-710 can track the motor temperature by monitoring current levels as well as detect abnormal conditions like line faults or undervoltage. Once an abnormal condition is detected, the SEL-710 sends a signal to the circuit breaker by opening or closing a contact, causing the breaker to open. Figure 1 shows a typical setup using the SEL-710 relay.

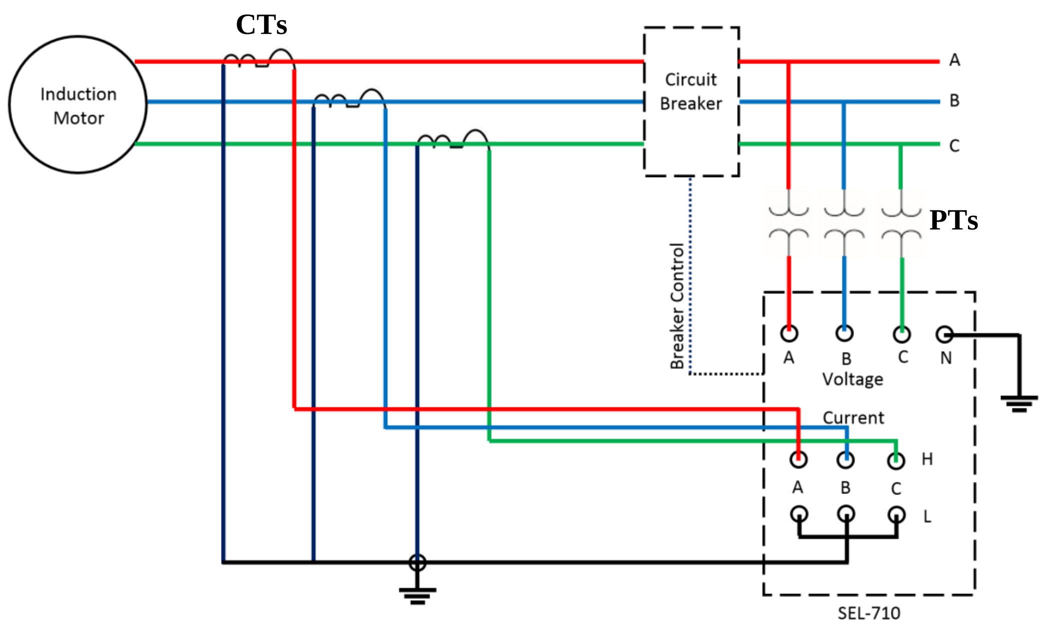

Figure 1: Motor protection configuration using a SEL-710.

The SEL-710 offers protection against a number of conditions, this lab will look into five of the most common. Operating the motor voltages below the rated value will cause excess current to flow into the motor resulting in excessive heating. The induction motor used in this lab is powered by three-phase voltages, the loss of a phase will result in an unbalanced system causing excessive heating to occur. We also want to protect against any fault conditions that occur. If too much torque is applied to the motor while running or starting, the machine will stall and enter a locked rotor state resulting in inrush level currents that are approximately three times the rated levels. Finally, we want to protect the motor against overheating from excessive starting or running above rated levels. The SEL-710 uses motor specifications to construct thermal curves which once reached, will trip the breaker.

Chapter 3: Requirements and Specifications

The requirements for this project keep consistent with Cal Poly lab methodology and achieve the desired learning objectives. The marketing requirements and specifications shown in Table 1 outline the project's scope.

TABLE I: LAB EXPERIMENT REQUIREMENTS AND SPECIFICATIONS

Marketing Requirements Covered	Engineering Specifications	Justification
2,4,5,6,7,8	Lab must include background documentation highlighting the importance of motor protection, types of conditions to protect against (locked rotor, thermal, fault, under voltage, and loss of phase). 3 page maximum.	Background information introduces students to motor protection and widens their scope of knowledge about the subject.
2,4,5,6,7,8	Lab must include a pre-lab assignment requiring students to perform calculations relevant to the lab procedure. Pre-lab should take no longer than 1 hour to complete.	Pre-lab assignment introduces students to calculations necessary to complete the lab.
2,11	Lab must include a high voltage safety warning before experimentation begins.	Experiment contains potentially lethal voltage/current levels. [3]
2,3,4,5,6,7,8	Lab must include a procedure instructing students how to program the relay to protect against locked rotor condition, motor thermal damage, faults, and loss of phase.	Procedure guides students to achieve desired learning objectives.
2,3,4,5,6,7,8	Lab must include a follow-up section containing experiment relevant questions to check for understanding.	Follow-up questions to reinforce key concepts and check for understanding.
2,3	Lab must include step-by-step relay setup and programming procedure.	Students must setup and program the relay to achieve desired protection schemes.
1,3	Lab computers must have acSELerator QuickSet programming software installed.	Students must program relay devices to achieve desired protection schemes.
1,2	Relay connections must interface with female banana connectors.	Standard connection cable for Cal Poly power labs. [10]
9	Project completion by December 2013.	Allows time to integrate into existing curriculum.
2,10	Experiment should take 2 hours and 50 minutes to complete.	Standard length of a Cal Poly lab period.

Marketing Requirements

1. Able to interface with existing equipment
2. Follows Cal Poly EE Lab format
3. Teaches students how to program relay devices

4. Teaches students how to protect against thermal damage
5. Teaches students how to protect against fault conditions
6. Teaches students how to protect against locked rotor conditions
7. Teaches students how to protect against loss of phase conditions
8. Teaches students how to protect against undervoltage conditions
9. Incorporate into Spring 2014 class
10. Able to finish experimentation in one lab session
11. Highlight any safety concerns

The requirements and specifications table format derives from [1], Chapter 3.

Chapter 4: Functional Decomposition

On the highest level, students participate in the lab, applying classroom knowledge and gain hands on experience with protection relaying. Figure 2 and Table 2 illustrate the project's level 0 black diagram and functionality.

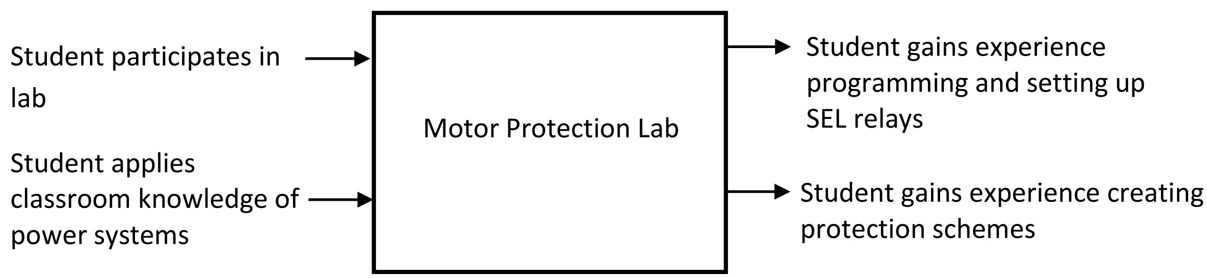

Figure 2: Lab Level 0 Box Diagram

TABLE II: LEVEL 0 LAB FUNCTIONALITY

Module	Motor Protection Lab
Inputs	• Student participation includes completing pre-lab calculations, experimental procedure, and follow up questions. • Students apply classroom knowledge of power system protection including relay operation, transformers, and fault analysis.
Outputs	• Student gains experience programming and setting up SEL relays • Student gains experience creating protection schemes for thermal, locked rotor, and fault conditions
Functionality	Upon completion of the lab (background, pre-lab, procedure, and follow-up questions), students have hands on experience with motor protection and relay programming.

Figure 3 on the following page illustrates the project's Level 1 box diagram with module functionality shown in Tables 3-6. Divided into four main modules, the lab contains background, pre-lab assignment, experiment procedure, and follow-up questions. The student performs background reading and pre-lab before class, experimental procedure during the lab period, and follow-up questions during lab report creation.

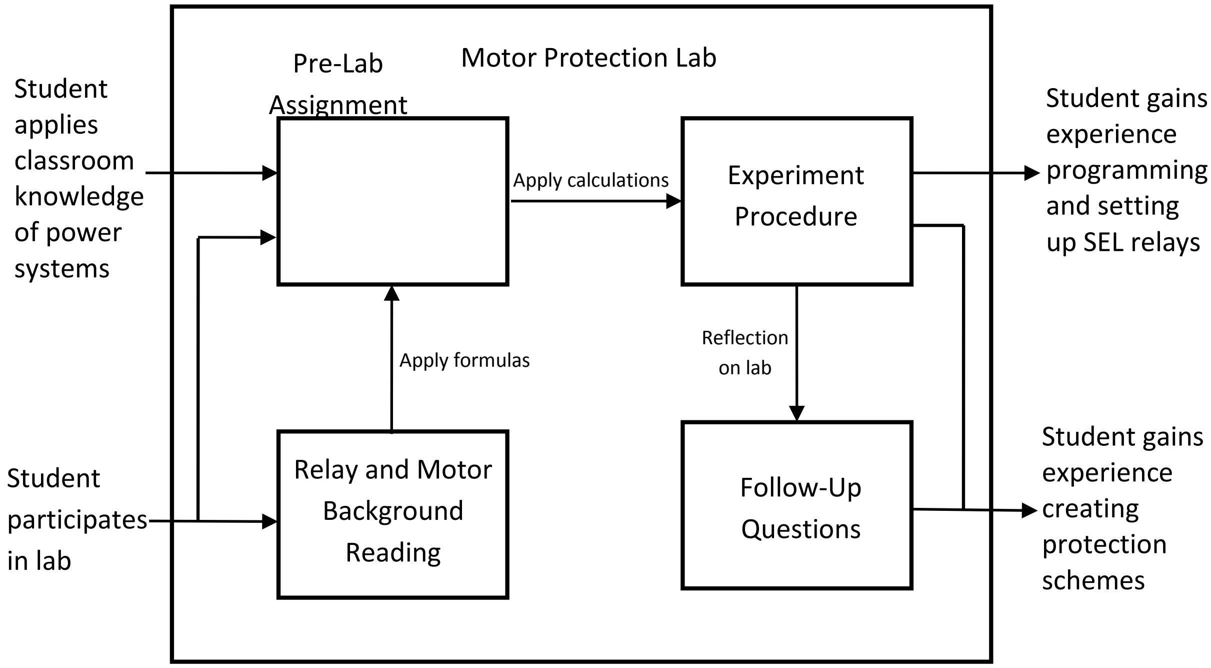

Figure 3: Lab Level 1 Box Diagram

Table III: Level 1 BACKGROUND

Module	Relay and Motor Background Reading
Inputs	• Students read the provided relay and motor background.
Outputs	• Students apply formulas and design concepts to the pre-lab, procedure, and follow-up questions.
Functionality	Students start the lab by reading the relay and motor background documentation, highlighting the importance of motor protection, types of conditions to protect against (locked rotor, thermal, and fault), and differences in electromechanical vs microprocessor based relays.

TABLE IV: LEVEL 1 PRE-LAB FUNCTIONALITY

Module	Pre-Lab Assignment
Inputs	• Students perform pre-lab calculations relevant to the lab procedure. • Students apply classroom knowledge of power system protection including relay operation, transformers, and fault analysis. • Students apply formulas and knowledge gained from lab background documentation.
Outputs	• Students apply calculations preformed in pre-lab to experiment procedure.
Functionality	Pre-lab allows the student to practice calculations needed during the procedure. The pre-lab can also be used to complete procedure steps before hand, allows for more experimentation time.

TABLE V: LEVEL 1 PROCEDURE

Module	Experiment Procedure
Inputs	• Students apply calculations preformed in pre-lab to achieve the desired protection schemes.
Outputs	• Students gain experience setting up and programming the SEL relay. • Students gain experience creating protection schemes for thermal, locked rotor, and fault conditions. • Students reflect on the lab's key concepts to answer follow-up questions
Functionality	The experimental procedure provides instruction on developing protection schemes, setting up and programming the relay.

TABLE VI: LEVEL 1 FOLLOW-UP

Module	Follow-Up Questions
Inputs	• Students reflect on the lab's key concepts to answer follow-up questions
Outputs	• Students gain experience creating protection schemes for thermal, locked rotor, and fault conditions.
Functionality	The follow-up questions reinforce the lab's key concepts, requiring the student to reflect on what the lab accomplished.

Chapter 5: Development and Construction

Once the conditions to protect against were selected, the next step was to determine the correct relay settings to program the SEL-710. The relay's manual contains examples and explanations of various protection schemes and proved a valuable resource in learning how to program the relay to operate correctly. The relay is controlled by setting a number of variables, Figure 4 shows the variables used to set several general motor attributes based on the circuit configuration.

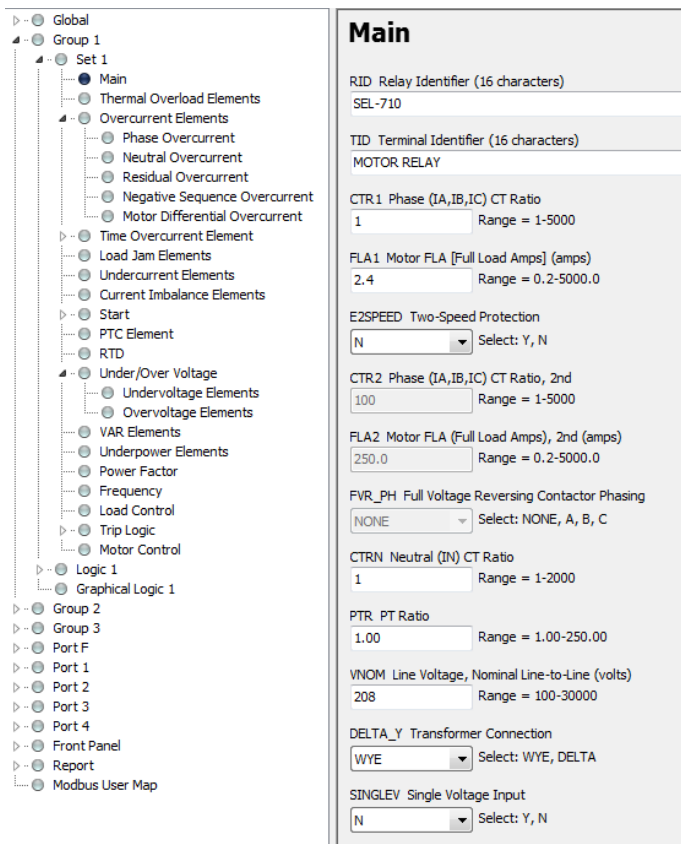

Figure 4: Settings used to set general motor attributes.

5.1 Undervoltage Protection

Before connecting anything to the SEL-710, the motor's voltage and current levels were compared to the relay's input limits. The motor's 208V was below the relay's rated continuous voltage of 300V so no voltage transformer was needed. The motor is rated at 2.4A full load which is below the relay's continuous rating of 15A so no current transformer was needed. Using this information, the values for the variables shown in Figure 4 were established.

The first protection scheme to be tested was undervoltage due to test circuit simplicity. The undervoltage trip level is a matter of preference, so a value of 70% rated voltage was selected. A Trip delay of 3 seconds was later chosen to coordinate with the 2 second locked rotor time, coordination is necessary due to the voltage drop across the resistors used to limit fault current. Figure 5 shows the variables used to set the undervoltage protection.

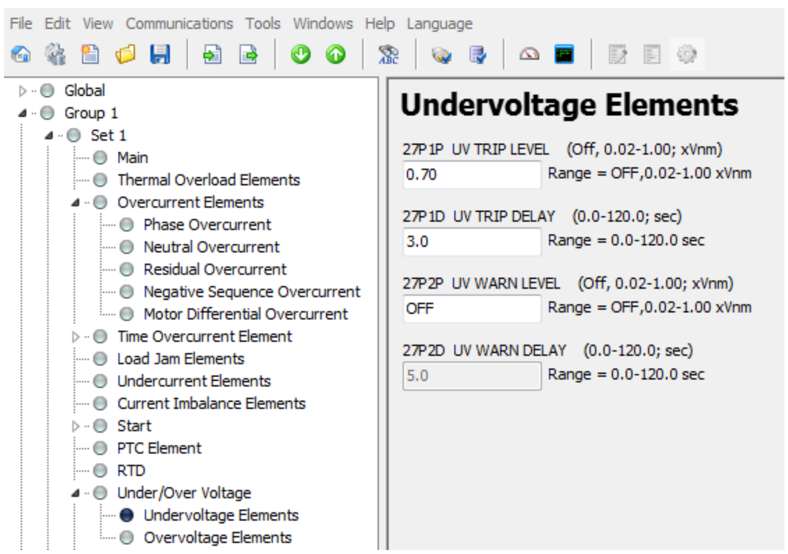

Figure 5: Settings used to protect against undervoltage conditions.

5.2 Loss of Phase Protection

Loss of phase protection was achieved by enabling the current imbalance elements shown in Figure 6. Under normal operating conditions, a 3 phase motor is balanced, if a phase is lost however, the circuit becomes unbalanced. An imbalance of 20% with 2 second delay was selected to account for any momentary or starting imbalances that may occur.

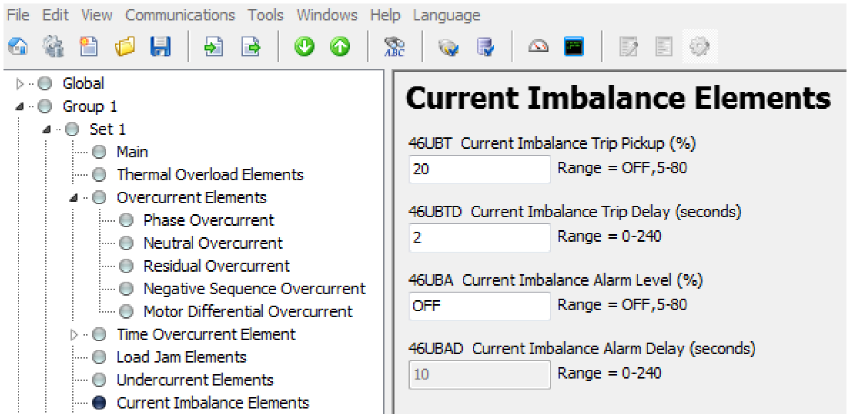

Figure 6: Settings used to protect against loss of phase.

5.3 Fault Protection

Fault protection is achieved using the instantaneous phase overcurrent element as shown in Figure 7. There are no downstream coordination issues with motors as they are end of line so instantaneous tripping is utilized. A value of 4x full load amps is selected, slightly higher than the 3x full load inrush current observed while starting. 10 Ohm resistors were added to the circuit to reduce fault current to approximately 11 amps so the lab bench fuses would not blow. Due to large fault current that may result in equipment damage, special warning and instructions are given to students in the procedure in case of misoperation.

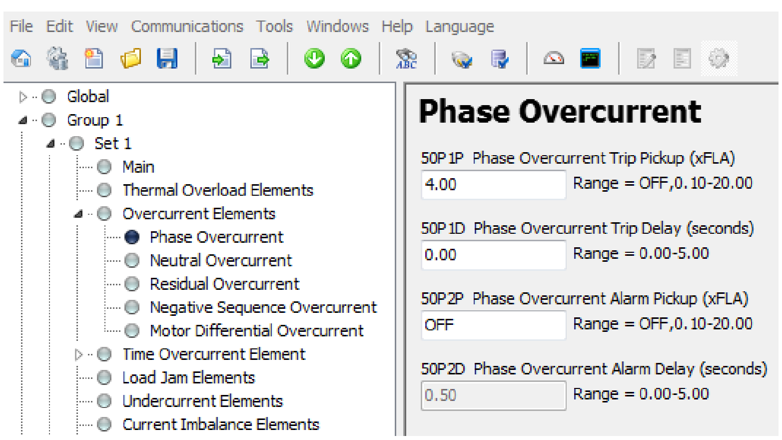

Figure 7: Settings used to protect against fault conditions.

5.4 Locked Rotor and Thermal Protection

Locked rotor and thermal protection is achieved using the thermal overload elements as shown in Figure 8. The SEL-710 calculates the motor's temperature using thermal curves based on motor specifications and the measured current. The three variables set in the thermal element are provided by the manufacturer and include service factor (SF), locked rotor amps as a multiple of full load current (LRA1), and locked rotor time (LRHOT1). Service factor is representative of how quickly the motor dissipates heat. Locked rotor amps indicates the motor current while in a stalled or starting state, this value is in terms of full load amps. Locked rotor time is the rated stall time before the motor overheats.

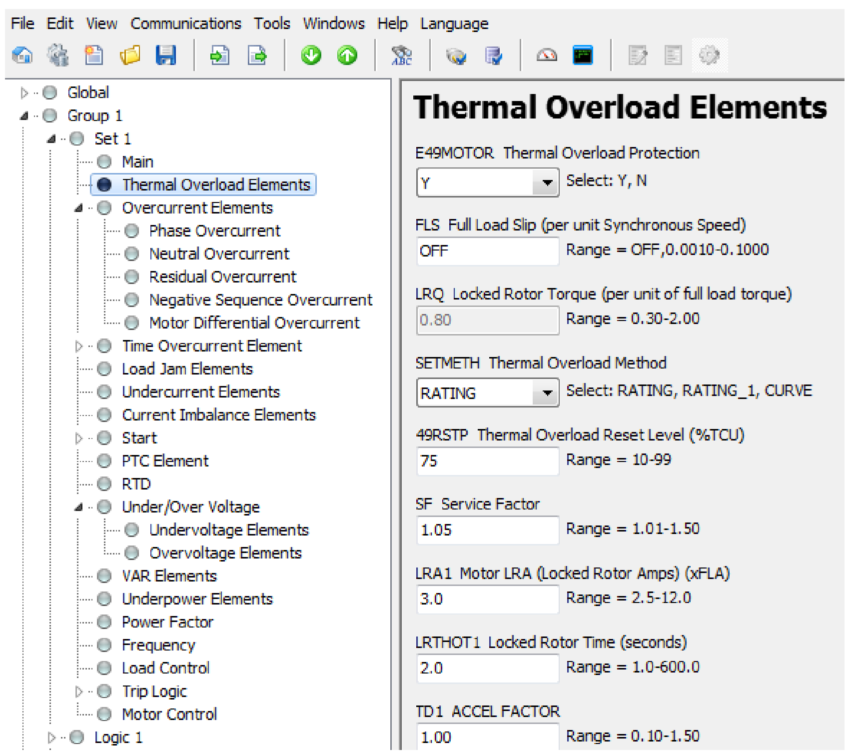

Figure 8: Settings used to protect against locked rotor and thermal overloads.

The thermal overload time can be calculated from equations given in the SEL-710 Manual. For current levels higher than full load and lower than locked rotor amps, trip time is given by the following equation:

$$T_P = \left[\frac{T_O * (TD + 0.2)}{\ln \left[\frac{{I_L}^2 - (0.9 * SF)^2}{{I_L}^2 - SF^2} \right]} \right] * \ln \left[\frac{I^2 - (0.9 * SF)^2}{I^2 - SF^2} \right]$$

where

T_O =	2	Locked Rotor time	(LRTHOT)
TD =	1	Acceleration factor	(TD1)
I_L =	7.2	Locked rotor current	(LRA1 * FLA1)
SF =	1.05	Service factor	(SF)
I =	$\frac{current}{2.4}$	Amps pu	

Using the equation above, students calculate trip time due to thermal overload, in the case of this lab, 3.4A was selected resulting in an overload time of approximately 120 seconds. Testing an actual thermal overload would cause excessive ware on the motors, so the trip time is calculated using the motor's present thermal level displayed on the relay's LCD screen. Once the relay detects an impending overload, a countdown timer appears on the relay's screen. For example, the student observes the thermal level at 50% and increases the current to 3.4A, the relay will detect an impending overload and start counting down from 60 seconds (50% of 120 seconds).

Two issues arose once the relay settings were established, how do students safely create fault conditions and how do we indicate relay operation. The SEL-710 relay is designed to detect abnormal conditions and trip a circuit breaker, the Cal Poly Electrical Engineering department currently does not possess relay controllable circuit breakers. The circuit shown in Figure 9 was developed to emulate the operation of an industrial size circuit breaker and is controllable by manual or relay operation.

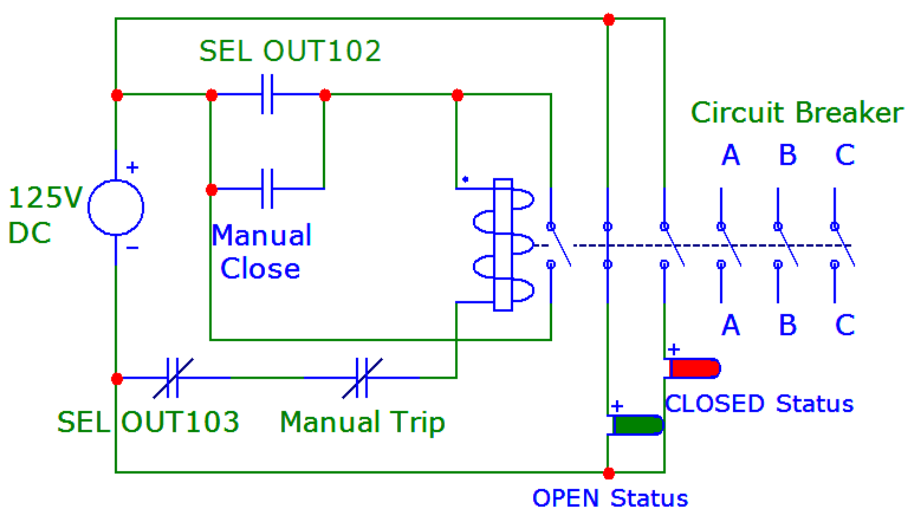

Figure 9: Relay controllable circuit breaker schematic.

The breaker was then combined with a manual 3 phase switch that can be utilized to safely create fault conditions or change the state of the system. Figures 10-12 on the following page show the finished breaker and fault box. Breaker control circuitry caries less than 0.25A and uses #16 AWG, circuit breaker and fault switch connections use #12 AWG and carry 3A continually and up to 12A momentarily. The breaker uses a 3 phase, 12A rated motor contactor from Schneider Electric with an auxiliary contact block, the 3 phase manual switch is rated up to 35A.

The breaker and fault box is constructed from a metal enclosure measuring 10x6x3 inches with Plexiglas cover. A grounding connection is attached to the box frame in case of accidental shorting. Red and green breaker position indicator lights were chosen to comply with standard industry coloring practices. Labeling was achieved using Cal Poly's laser etcher then filling in with paint. All connections are banana/spade terminal blocks to comply with standard equipment connections in Cal Poly's power laboratory. Seven boxes were constructed to supply all laboratory benches. A special thanks to Schneider Electric for their generous donation of motor contactors, auxiliary contact blocks, and manual switches.

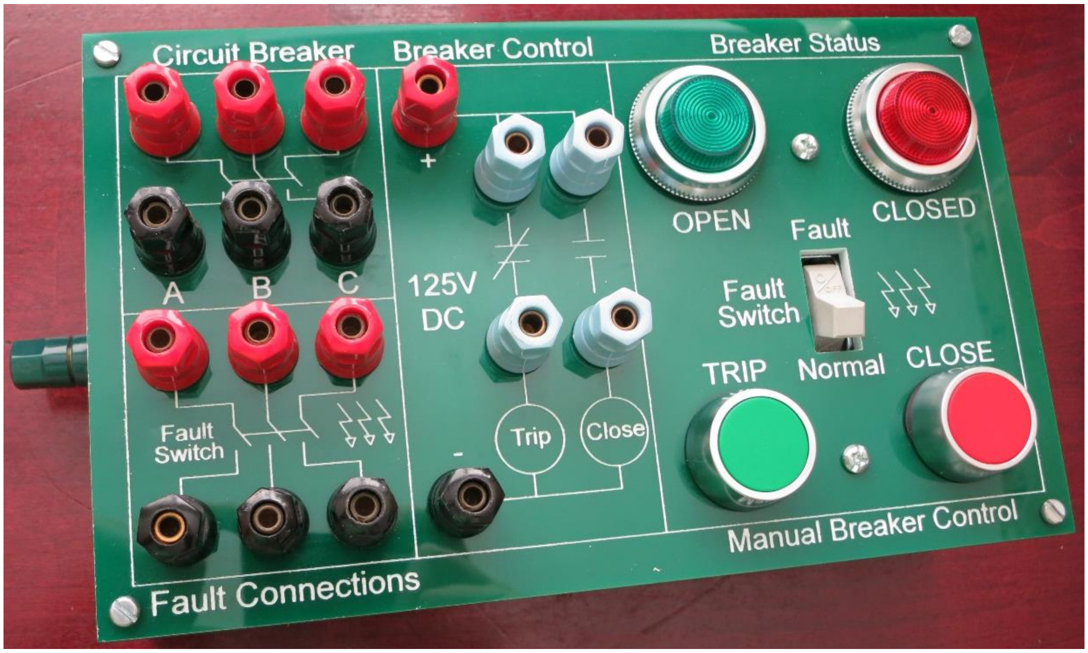

Figure 10: Breaker and fault box top view.

Figure 11: Breaker and fault box side view.

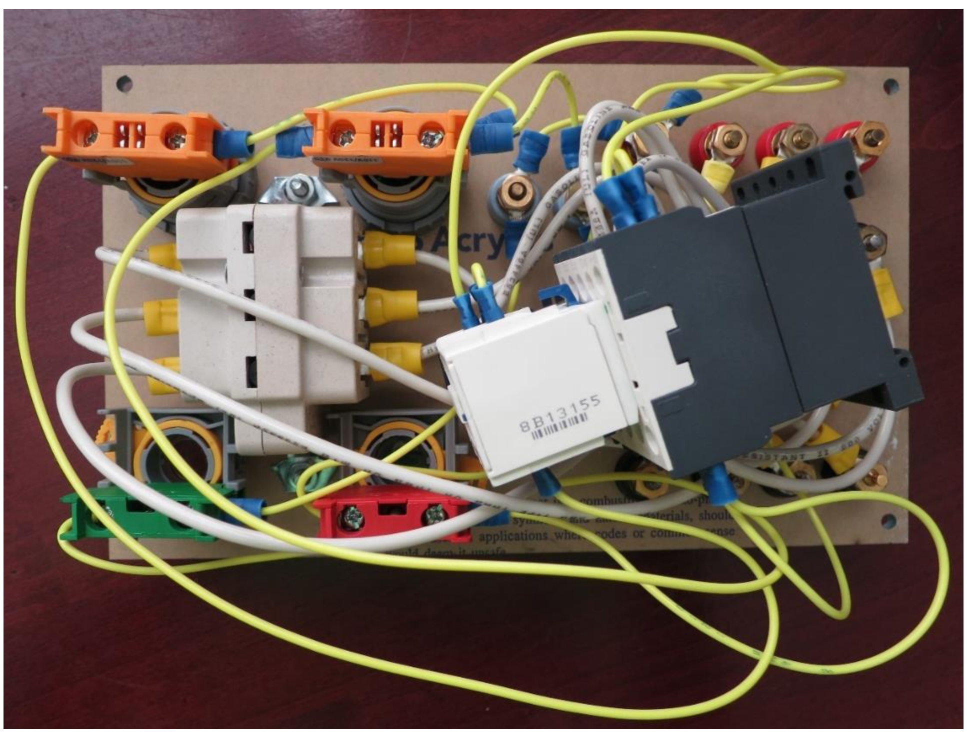

Figure 12: Breaker and fault box inside view.

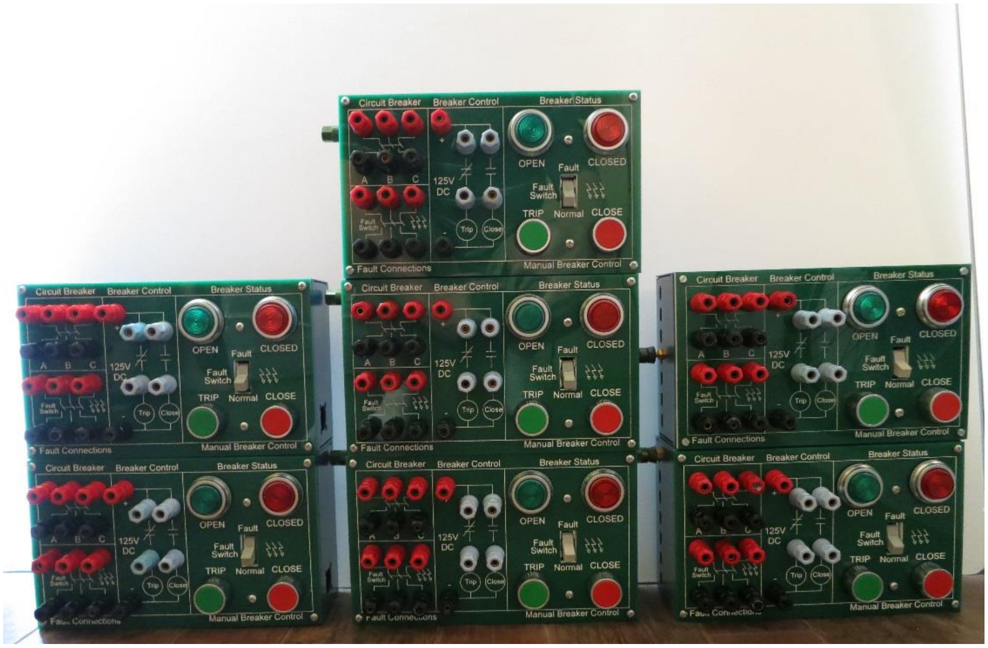

Figure 13: Seven breaker and fault boxes to equip the entire power lab.

Chapter 6: Integration and Test Results

Following the procedure outlined in steps 1-8 of the laboratory experiment document found in Appendix A, I successfully established connections to the SEL-710 relay then proceeded to setup the test circuit found in Figure 14.

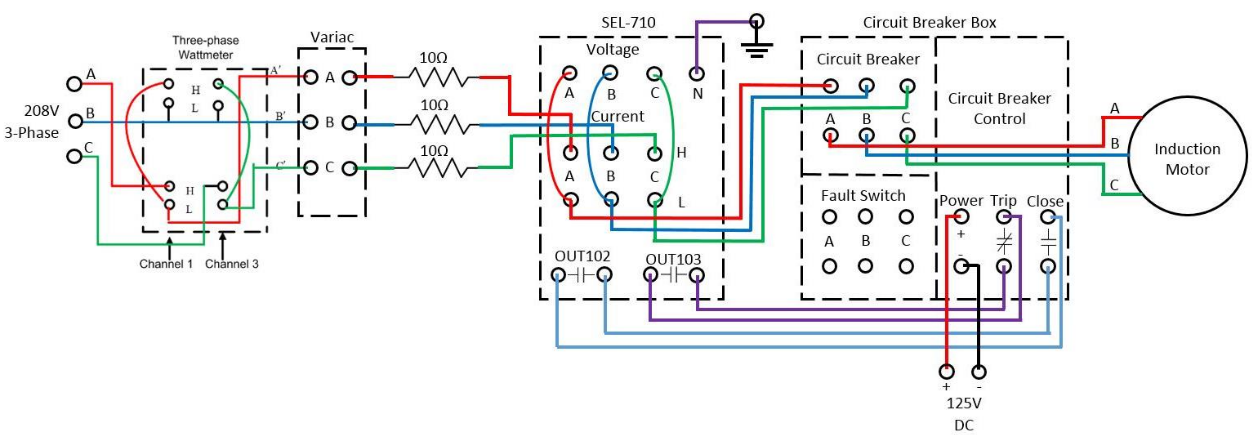

Figure 14: Normal operation circuit for lab experiment.

Following the procedure outlined in steps 9-10 of Appendix A, the relay correctly identified and tripped for an undervoltage condition as seen in Figure 15. The digital 27P1T asserts at 5 cycles indicating an undervoltage condition. The TRIP digital asserts at the same time and then the trip bit OUT103 asserts 0.25 cycles later. The current waveforms start to collapse 1-2 cycles later as the breaker opens.

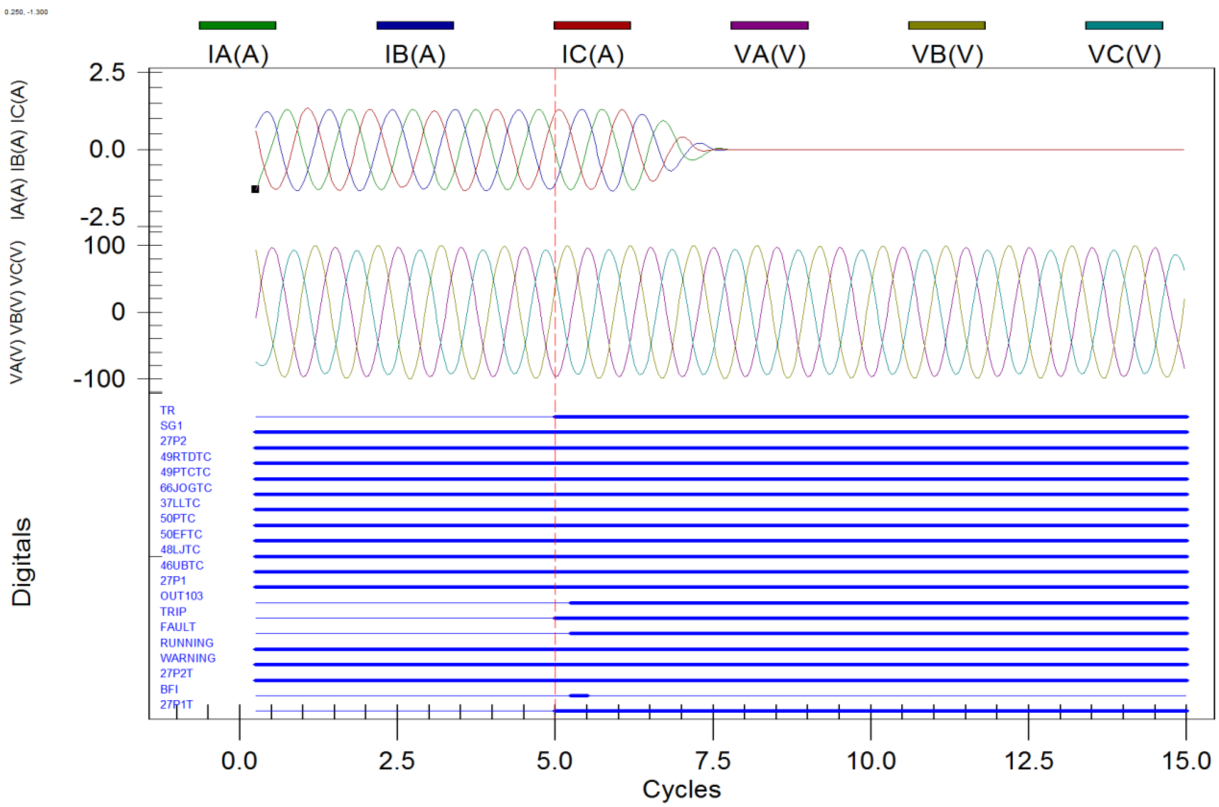

Figure 15: Undervoltage event report.

Following the procedure outlined in steps 12-14 of Appendix A, the relay correctly identified and tripped for a loss of phase A as seen in Figure 16. The digital 46UBT asserts at 5 cycles indicating a phase imbalance condition. The TRIP digital asserts at the same time and then the trip bit OUT103 asserts 0.25 cycles later. The current waveforms start to collapse 1-2 cycles later as the breaker opens.

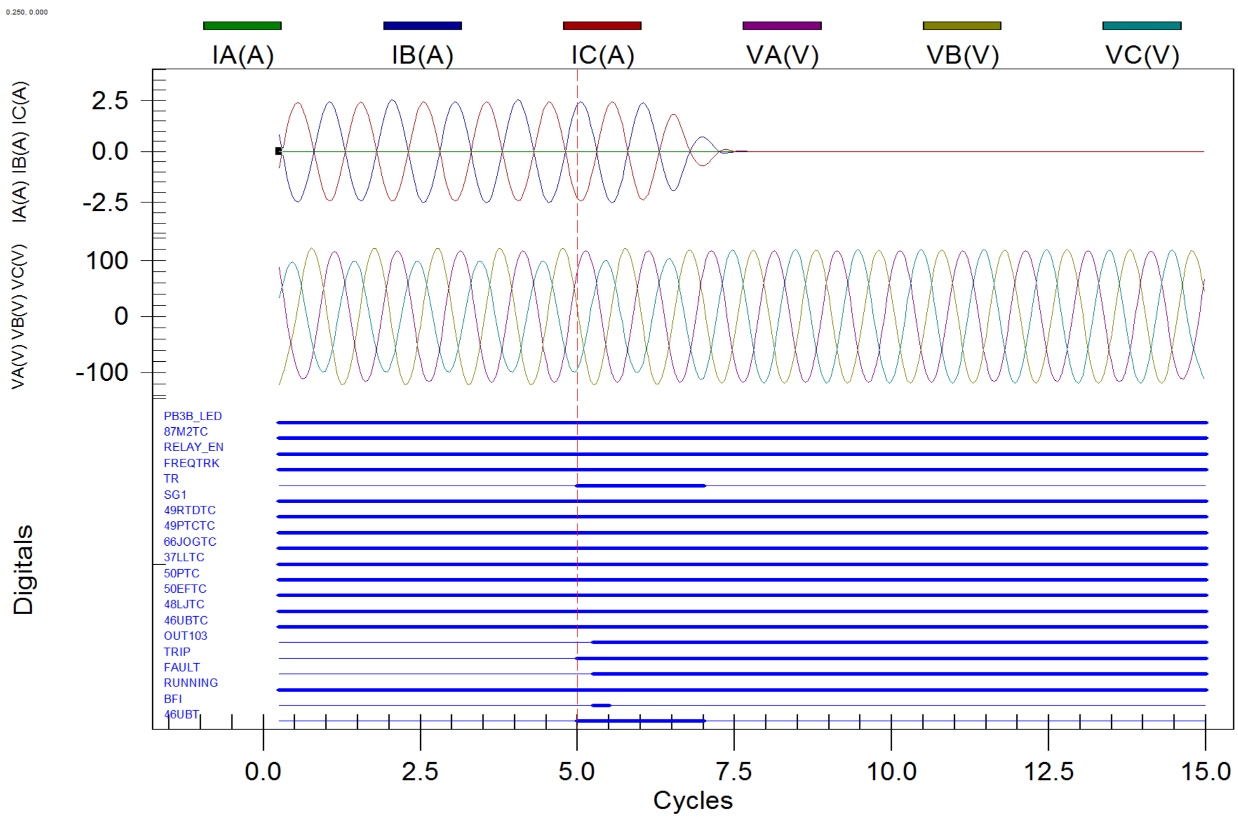

Figure 16: Loss of phase event report.

Following the procedure outlined in steps 15-17 of Appendix A, the relay correctly identified and tripped for an A-B phase fault as seen in Figure 17. The digital 50P1T asserts at 5 cycles indicating an instantaneous phase overcurrent condition. The TRIP digital asserts at the same time and then the trip bit OUT103 asserts 0.25 cycles later. The current waveforms start to collapse 1-2 cycles later as the breaker opens.

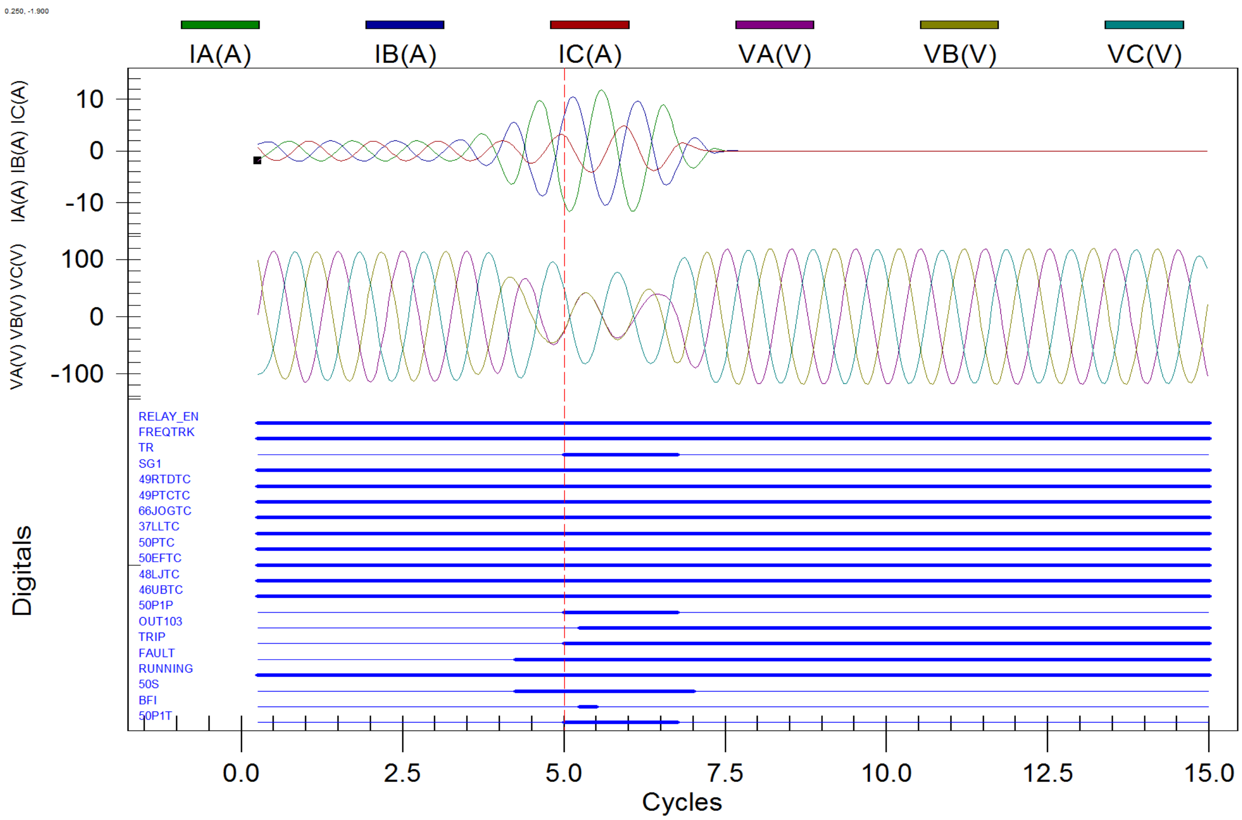

Figure 17: Phase to phase fault (A-B) event report.

Following the procedure outlined in steps 18-20 of Appendix A, the relay correctly identified and tripped for a locked rotor condition as seen in Figure 18. The digital 49T_RTR asserts at 5 cycles indicating a locked rotor condition. The TRIP digital asserts at the same time and then the trip bit OUT103 asserts 0.25 cycles later. The current waveforms start to collapse 1-2 cycles later as the breaker opens.

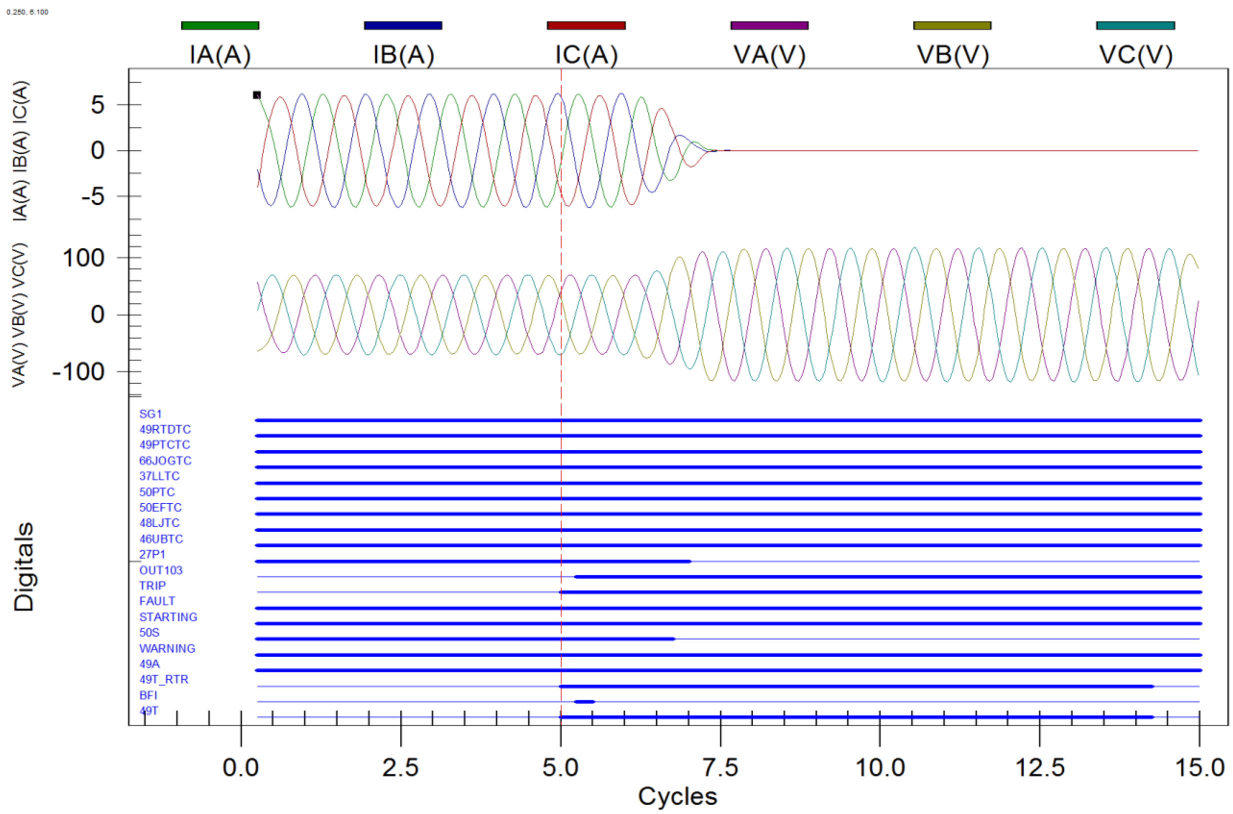

Figure 18: Locked rotor event report.

Following the procedure outlined in steps 21-24 of Appendix A, I observed a motor temperature 66% of the thermal limit and a countdown timer of 36 seconds compared to the theoretical 39 seconds from the following equation:

$$T_p = 120 * (100 – \text{present motor temperature } \%)$$

Chapter 7: Conclusion

With the equipment donation from Schneider Electric, we are able to perform experiments previously unavailable due to large current levels or inability to change system states. With enough equipment to supply all benches with a breaker and fault box, new possibilities are opened not only for this lab experiment but for others involving SEL equipment as well. This lab experiment provides an introduction to microprocessor based relay protection that gives student’s hands on experience relevant to industry practices.

Personally, I have increased my understanding of motor protection greatly in doing research for this project and hope students feel the same after completing the laboratory experiment. The experiment provided real world examples of protection concepts learned during power systems class EE407 and expanded on it with concepts like thermal protection. Gaining insight into motor thermal levels and how to calculate them answers questions raised in earlier classes such as “I am asked to run at 110% rated torque, am I going to break this machine?”

Another lesson learned from this project is the importance of planning ahead. Deciding to add a breaker and fault box added a considerable amount of work to the project. The biggest issue however was finding time to use Cal Poly’s laser etcher as the machine normally required reservations 2 weeks before hand. The addition of the breaker and fault box also allowed me to experience the process involved in seeking donations. The process of procuring the donated equipment from Schneider Electric took approximately 3 months from first contact to equipment pickup, once again emphasizing the importance of starting early and planning for delays.

Chapter 8: References

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APPENDIX A – LABORATORY EXPERIMENT DOCUMENT

ELECTRICAL ENGINEERING DEPARTMENT
California Polytechnic State University
San Luis Obispo

EE 444 **Experiment #**

Induction Motor Protection using SEL-710

Introduction:

In this lab you will use the SEL-710 microprocessor based relay by Schweitzer Engineering Laboratories to protect against the following conditions:

1. Under-voltage
2. Loss of phase
3. Line-to-line fault
4. Locked rotor
5. Thermal overload

Depending on the size and importance of the motor, protection may be implemented in various ways ranging from a single-trip overcurrent breaker to a microprocessor controlled breaker with current and voltage monitoring. The SEL-710 is a microprocessor controlled protection relay that reads the voltage and current levels of the lines feeding the motor allowing it to monitor the motor's condition. The SEL-710 can track the motor temperature by monitoring current levels as well as detect abnormal conditions like line faults. Once an abnormal condition is detected, the SEL-710 sends a signal to the circuit breaker by opening or closing a contact, causing the breaker to open. Figure 1 shows a typical setup using the SEL-710 relay.

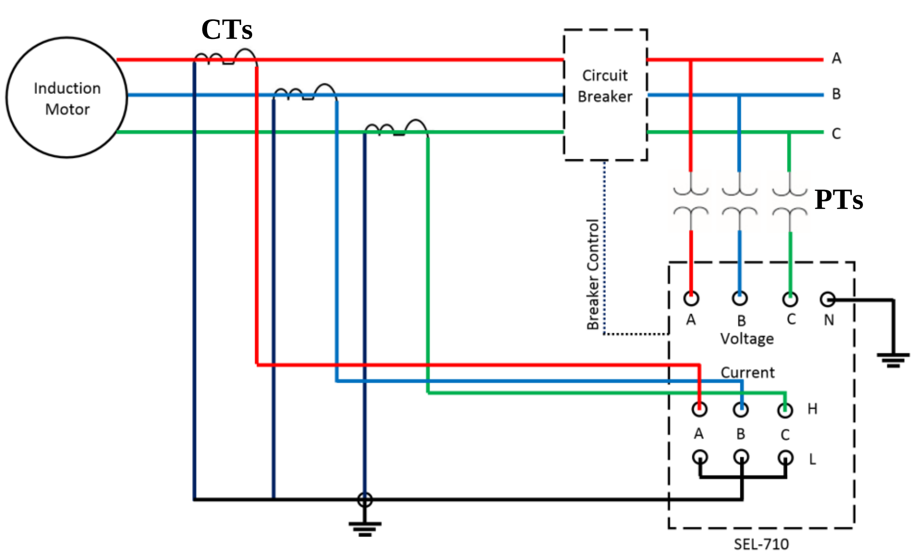

Figure 1: Typical motor protection configuration using a SEL-710.

The SEL-710 offers protection against a number of conditions, this lab will look into five of the most common. Operating the motor voltages below the rated value will causes excess current to flow into the motor resulting in excessive heating. The induction motor used in this lab is powered by three phases, the loss of a phase will result in an unbalanced system causing excessive heating to occur. We also want to protect against any fault conditions that occur. If too much torque is applied to the motor while running or starting, the machine will stall and enter a locked rotor state resulting in inrush level currents that are approximately three times the rated levels. Finally, we want to protect the motor against overheating from excessive starting or running above rated levels. The SEL-710 uses motor specifications to construct thermal curves which once reached, will trip the breaker.

In this lab you will use the relay controllable circuit breaker shown in Figure 2. We see the breaker uses two SEL controlled contacts, the normally-open "SEL OUT102" and the normally-closed "SEL OUT103". Utility-size circuit breakers are more complicated and contain separate circuitry for the tripping and closing mechanisms, they are however similar in the fact that tripping is achieved using a single contact and closing with another. The breaker has two means of tripping/closing, SEL controlled and manual operation. In the utility industry, green is normally used for OPEN and red for CLOSED. Can you follow the circuit diagram shown in Figure 2?

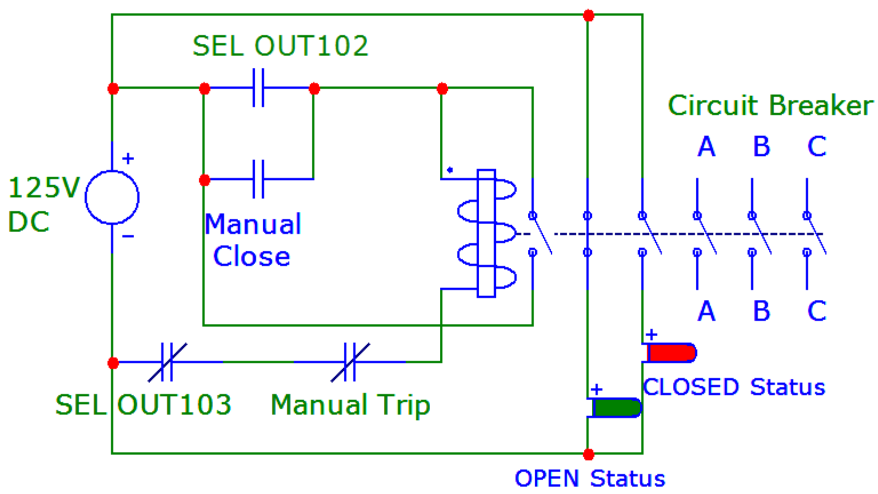

Figure 2: Relay Controllable Breaker Diagram.

<u>Equipment List:</u>

Banana to Banana Wires (26)
Bag of Short Leads (3)
10 ohm, 6A Resistors (3)
Relay Controllable Circuit Breaker and Fault Box (1)
3-Phase Induction Motor (1)
Schweitzer SEL-710 Motor Protection Relay (1)
Yokogawa Power Meter (1)

<u>Prelab:</u>

Note: The prelab requires you to utilize the SEL-710 manual, if you are unsure what something is or does, try searching for it. A good place to start is Section 4: Protection and Logic Functions.

1. What considerations should be taken into account in coordinating motor protection with other equipment?

   Answer: No coordination issues, motor is end of line so instantaneous overcurrent can be used.

2. What does enabling fail-safe on an output contact do?

   Answer: When fail-safe is enabled the contact is normally closed (NC) and will open when asserted. For this experiment, the breaker-close contact OUT102FS = N (making it a NO contact), and the breaker-trip contact OUT103FS=Y (making it a NC contact). Refer to Page 53 of the SEL-710 manual for details.

3. Find the locked rotor trip time for the following conditions.

CTR = PTR = 1	CT / PT Ratio
DELTA_Y = WYE	Transformer Connection
FLA1 = 2.4	Full Load Amps
E49MOTOR = Y	Enable Thermal Protection
SETMETH = RATING	Calculation Method
49RSTP = 75	Thermal Overload Reset Level
SF = 1.05	Service Factor
LRA1 = 3.0	Locked Rotor Amps (xFLA)
LRTHOT1 = 2.0	Locked Rotor Time
TD1 = 1.00	Acceleration Factor
RTC1 = AUTO	Stator Time Constant
Measured locked rotor current = 7.2A	

   Answer: 2 Seconds. Measured current = LRA1, therefor trip time = LRTHOT1. See SEL-710 Manual Page 480 for equations.

4. Using the settings above, find the thermal overload trip time for a current of 3.4A

   Answer: 124 seconds. See SEL-710 Manual Page 480.

$$T_P = \left[\frac{T_O * (TD + 0.2)}{\ln\left[\frac{{I_L}^2 - (0.9 * SF)^2}{{I_L}^2 - SF^2}\right]}\right] * \ln\left[\frac{I^2 - (0.9 * SF)^2}{I^2 - SF^2}\right]$$

Where

T_O =	2	Locked Rotor time	(LRTHOT)
TD =	1	Acceleration factor	(TD1)
I_L =	7.2	Locked rotor current	(LRA1 * FLA1)
SF =	1.05	Service factor	(SF)
I =	$\frac{3.4}{2.4} = 1.42$	Amps pu	(3.4 / FLA1)

$$T_P = \left[\frac{2 * (1 + 0.2)}{\ln\left[\frac{7.2^2 - (0.9 * 1.05)^2}{7.2^2 - 1.05^2}\right]}\right] * \ln\left[\frac{I^2 - (0.9 * 1.05)^2}{I^2 - 1.05^2}\right]$$

$$T_P = 582.5 * \ln\left[\frac{I^2 - 0.893}{I^2 - 1.103}\right]$$

$$T_P = 582.5 * \ln\left[\frac{1.42^2 - 0.893}{1.42^2 - 1.103}\right] \quad = \quad 124\ seconds$$

Procedure:

1. Make sure the SEL-710 is connected via serial cable to the computer.

2. Run AcSELerator Quickset and connect the computer to the SEL-710 relay.
   a. Under *Communications* -> *Parameters*, verify the following settings:

Active Connection Type	Serial
Device	COM??? (Determined once lab is set up)
Data Speed	19200
Data Bits	8
Stop Bits	1
Parity	None
RTS/CTS	Off
DTR	On
XON/XOFF	On
Level One Password	OTTER
Level Two Password	TAIL

   *If you are unable to connect, you can view the relay's communication settings on the SEL-710 screen by: *ENT* -> scroll down to *Set/Show* -> *Port* -> **(Determined once lab is set up)** -> *Comm Settings*. To exit, continue to press *ESC*. You may need to restart AcSELerator before it will connect.

   b. Ensure you are connected to the relay by verifying it says "Open: Connected" at the bottom of the screen.
   c. Click on the Terminal Window icon on the toolbar or press (Ctrl + T).
   d. Type *ID* and press enter to bring up the relay's information.
   e. Record the FID and PARTNO strings and exit out of the Terminal Window.

3. Create a new settings file.
   a. On the AcSELerator Quickset menu click on *New*.
   b. Select the Device Family, Model, and Version based on the FID you recorded from the Terminal Window.
   c. Select the relay options based on the PARTNO you recorded from the Terminal Window.

4. Using the circuit shown in Figure 3, your motor's rated voltage and current, a service factor of 1.05, locked rotor amps of 3x full load amps, a locked rotor time of 2 seconds, a current imbalance of 20% with 2 second delay, a under-voltage of 0.7pu with 4 second delay, a normally-closed Trip contact, and finally a normally-open Close contact, determine the relay settings for the following fields:

- Global
    - General
        - PHROT = ACB_
- Group 1
    - Set 1
        - Main
            - CTR1 = _____ 1
            - FLA1 = _____ 1.4 or 2.4 depending on motor
            - CTRN = _____ 1
            - PTR = _____ 1
            - VNOM = _____ 208
            - DELTA_Y = _____ WYE
        - Thermal Overload Elements
            - E49MOTOR = Y____
            - SF = _____ 1.05
            - LRA1 = _____ 3.0
            - LRTHOT1 = _____ 2.0
        - Overcurrent Elements
            - Phase Overcurrent
                - 50P1P = _____ ~ 25% over Locked Rotor Amps
                - 50P1D = _____ 0
        - Current Imbalance Elements
            - 46UBT = _____ Default 20% OK
            - 46UBTD = _____ ~ 2
        - Under / Over Voltage
            - Undervoltage Elements
                - 27P1P = _____ 70
                - 27P1D = _____ 3
    - Logic 1
        - Slot A
            - OUT102FS = _____ N
            - OUT103FS = _____ Y

5. Upload your settings to the relay by clicking *File -> Send*.

6. Construct the circuit shown in Figure 3 on the following page. Set the Variac full so the voltage is 1:1.

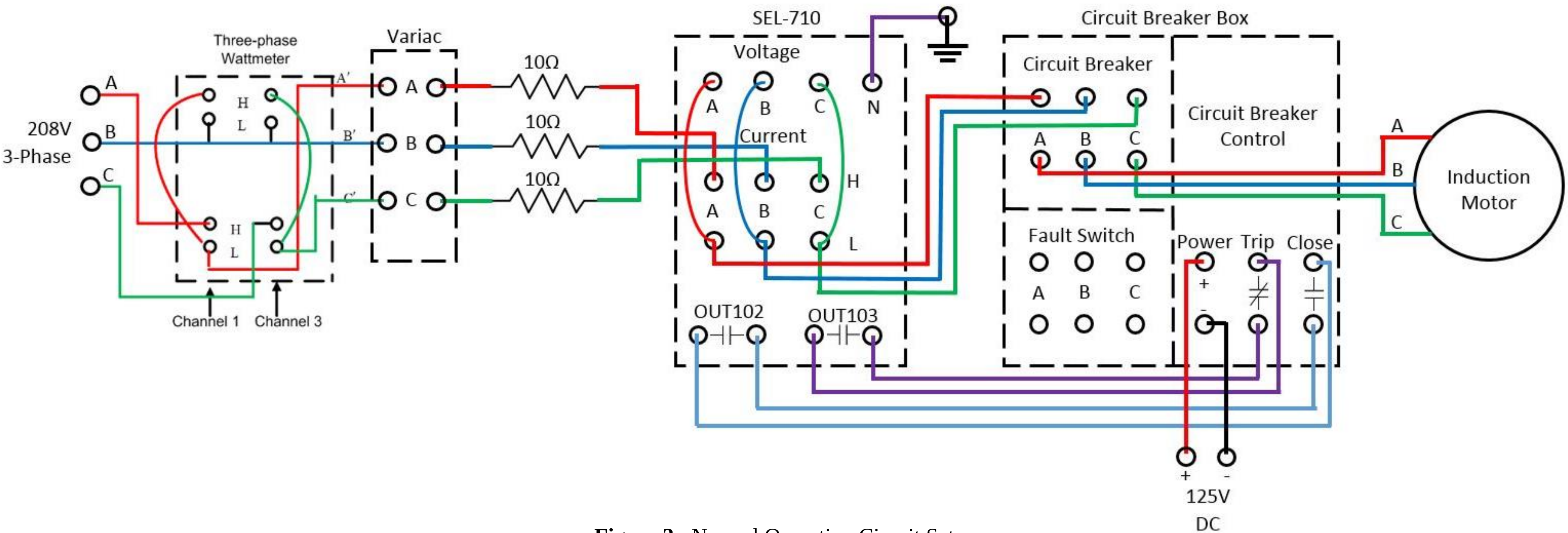

Figure 3: Normal Operation Circuit Setup

7. Verify your relay settings and circuit with the professor.

8. Verify you can Close and Trip the breaker using the red/green push buttons on the breaker box as well as the "Start" and "Stop" buttons on the SEL-710.

9. Test your under-voltage settings by starting the motor and reducing the Variac until the relay trips at a voltage of 0.7 pu. Restore the voltage to 1.0 pu after the relay trips.

10. Retrieve the Event Report by clicking *Tools -> Events -> Get Event Files*.
    a. Select the event created on today's date and click *Get Selected Events*.
    b. Save the Event report to the desktop and then open the file.
    c. Click on *Pref* at the bottom of the event report, then click *Select Active Digitals*, and finally *OK*. The Event Report should resemble Figure 4.
    d. Verify the relay operated correctly and print the Event Report.

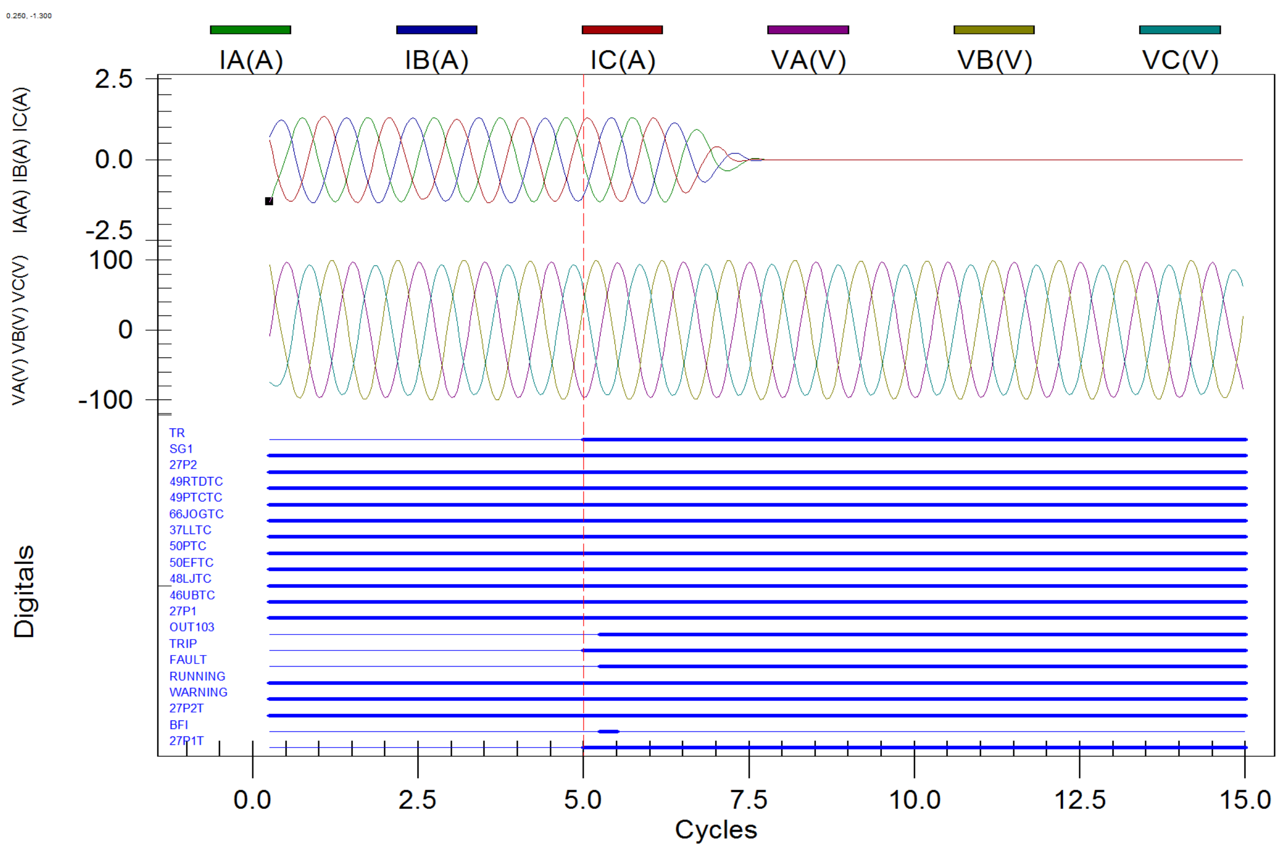

Figure 4: Event Report displaying current, voltage, and active digitals.

11. To view the Phasor Diagram, verify the correct phase rotation by clicking *Options*, select *ACB rotation*, and hit *OK*. Finally, click on  in the Analytic Assistant. You can step through the event by hitting the side arrow under *Data Selection*.

12. Next, test your Loss of Phase settings by opening phase-A using the fault switch. Turn off the AC and DC power and move the phase-A connections as shown in Figure 5. The fault switch should be closed in the up position toward “Fault”. Verify your circuit with the professor.

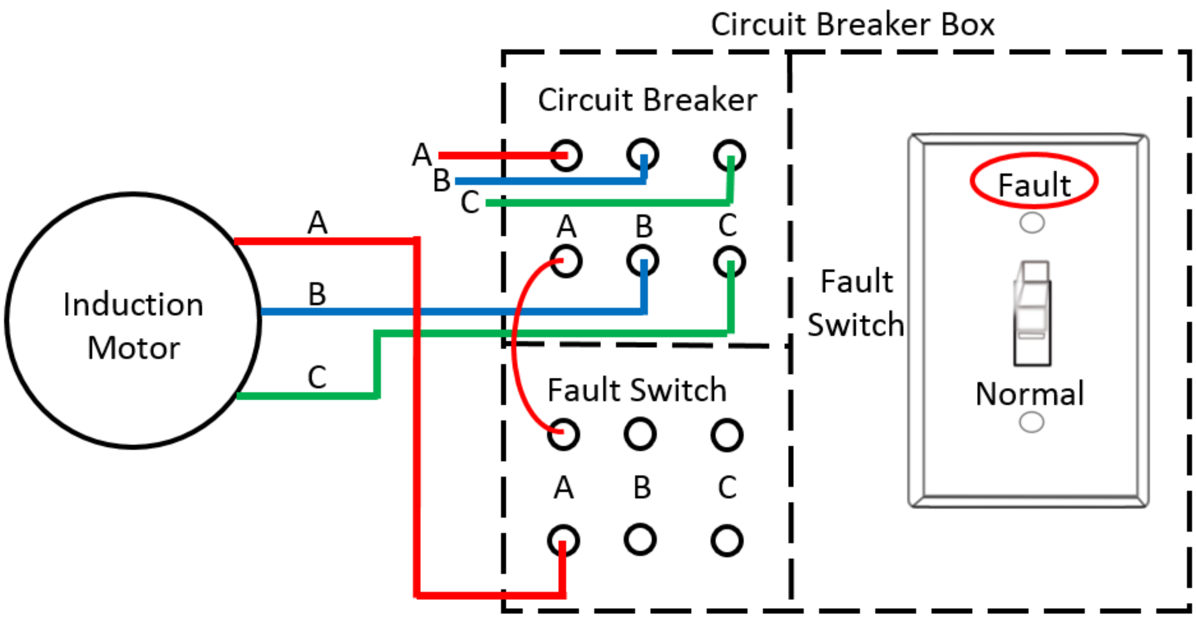

Figure 5: Loss of Phase-A Circuit

13. Turn on the AC and DC power and start the motor. Open the Fault Switch by toggling it down toward the “Normal” position. The relay should trip in 2 seconds.

14. Retrieve the Event Report as before, verify correct operation, then print.

15. Next, test your Fault settings by creating a phase-A to phase-B fault. Turn off the AC and DC power and construct the circuit shown in Figure 6. The fault switch should be open in the down position toward "Normal". Verify your circuit with the professor.

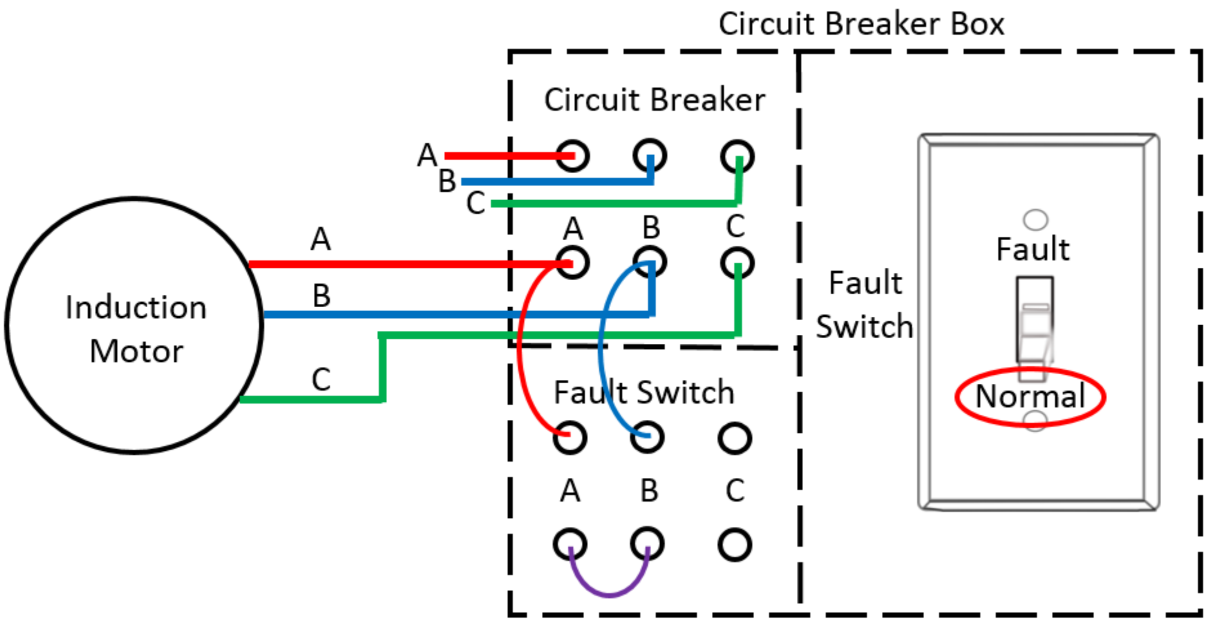

Figure 6: Phase to Phase Fault (A-B) Circuit

WARNING: This test causes fault currents that will damage equipment if they persist for more than a few seconds. Your instantaneous overcurrent time should be set at a zero second delay. If the relay does not trip after 1 second, cut power to the circuit.

16. Turn on the AC and DC power and start the motor. Close the Fault Switch by toggling it up toward the "Fault" position. The relay should trip instantaneously.

17. Retrieve the Event Report as before, verify correct operation, then print.

18. Next, test your Locked Rotor settings. Turn off the AC and DC power and construct the circuit shown in Figure 7. Increase the applied torque to the motor to maximum by turning the torque dial clockwise until it stops and verify the switch is on. Verify your circuit with the professor.

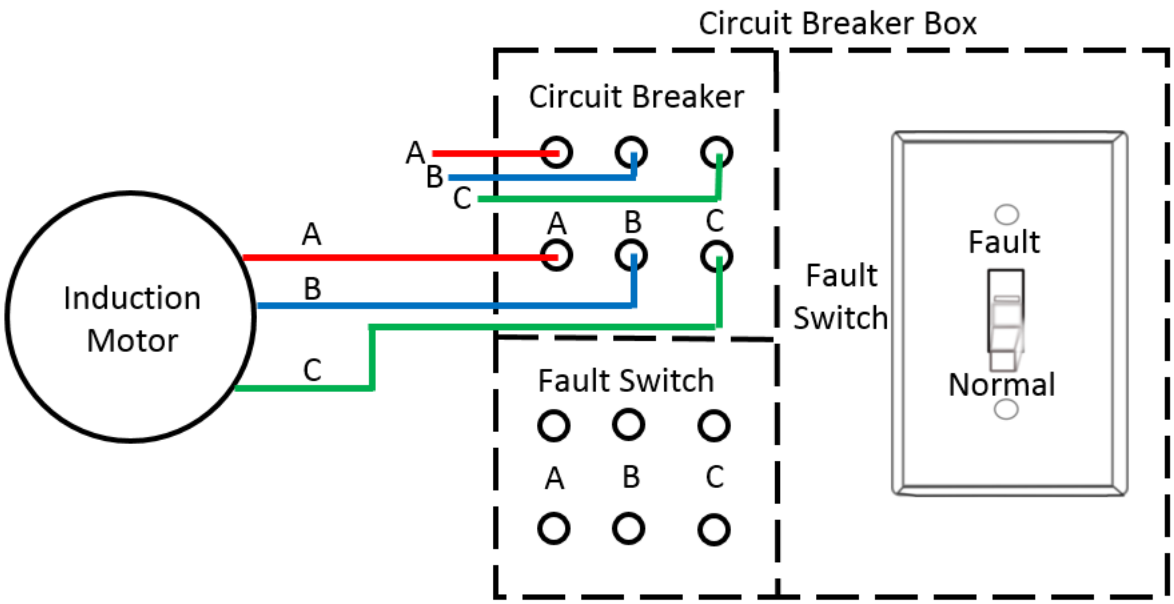

Figure 7: Normal Operation Circuit

WARNING: This test causes inrush currents that will damage equipment if they persist for more than a few seconds. Your locked rotor time should be set at 2 seconds. If the relay does not trip after 3 seconds, cut power to the circuit.

19. Turn on the AC and DC power. Start the motor, it should be in a locked rotor state and not spinning. The relay should trip in 2 seconds.

20. Retrieve the Event Report as before, verify correct operation, then print.

21. Next, test your Thermal Overload settings. The circuit is the same as the previous test but you need to reduce the torque to zero by turning the dial completely counter-clockwise.

22. Start the motor and record the Stator TCU % displayed on the SEL-710 display. This value is the thermal level the motor is presently at of the motor's maximum thermal level. As you found in the pre-lab, the motor can run for ~120 seconds at a current of 3.4A (if your motor is rated at 2.4A). If your TCU % reads 50%, this means the motor can only run for 60 seconds at 3.4A. When the relay senses an impending overload, it will display a countdown timer on the screen. Once your TCU % is recorded increase torque to the rated full load of 12 inch-pounds.

    WARNING: This test produces overload currents that causes the motor to overheat resulting in possible damage if applied for too long. If torque is applied to quickly and the motor stalls, cut power the circuit.

23. Have one student watch the SEL-710 display for the countdown timer while the other increases the torque until the Watt meter reads 3.4A. Do not increase torque too quickly or the motor will stall but do not go to slowly either as the motor is not designed for these current levels. Once the current reaches 3.4 amps, record the time on the countdown and reduce the torque to safe levels.

24. Compare the theoretical and experimental trip times.

<u>Report:</u>

1. Fill out and include your relay settings shown in step 4 of the procedure.

2. For each event report:
    a. Describe how the waveforms match what you expect for the given condition.
    b. Describe how you know the relay operated correctly.

3. Compare the theoretical and experimental trip times for the thermal overload condition.

APPENDIX B - EXPENSES

Project expenses include breaker box materials and time, Cal Poly already owns the SEL-710 relay and 3-Φ induction motor used in the experiment. Table 7 outlines the breaker box material list, values in parenthesis indicate materials obtained through Cal Poly's EE department and are estimates.

TABLE VII: BREAKER BOX MATERIAL LIST

Discription	Manufacturer	Model	Price
1x 3-Φ Motor Contactor 12A 125VDC Coil	Schneider Electric	LP1K1210GD	$106
1x Auxiliary Contact Block	Schneider Electric	LA1KN22M	$14
1x 3-Φ Manual Switch	Schneider Electric	2510KO2	$135
1x 125VDC Green Indicator Light	Alpinetech	PLN-30G	$11
1x 125VDC Red Indicator Light	Alpinetech	PLN-30R	$11
1x Green Push Button Switch - 1NC	Alpinetech	PBF-22G	$8
1x Red Push Button Switch - 1NO	Alpinetech	PBF-22R	$8
7x Red Banana Termination Block			($3.50)
7x Black Banana Termination Block			($3.50)
4x Blue Banana Termination Block			($2)
1x Green Plexiglas – 10x6			($2)
1x Metal Project Box – 10x6x3			($10)
	Total	**per bench**	**$314**
	Total	**(7 benches)**	**$2,198**

Based on project length and workload, an estimated 5.5 hrs/week have been allocated for experiment development and construction using the following equation:

$$Hours\ per\ week = \frac{t_a+4t_m+t_b}{6} = 5.5$$ [1] Ch. 10, Eq. 6

where

Optimistic estimate	t_a = 3 hrs/week
Pessimistic estimate	t_b = 10 hrs/week
Realistic estimate	t_m = 5 hrs/week

Total Labor Cost = 5.5 hrs/week * 30 weeks * $20/hr

Total Labor Cost = $3,300

To equip additional benches, SEL-710 relays, induction motors, and breaker box parts can be purchased at an approximant cost of:

SEL-710 Relay	$2,500
1/3hp, 3-Φ Induction Motor	$750
Breaker Box	$314

Total Cost per Additional Bench = $3,564

APPENDIX C – SCHEDULE

The Gantt chart shown in Figure 19 outlines the project's timeline. Project planning occurs during EE460 and development progresses over EE463 and EE464. The timeline contains three iterations of research and experimentation, two in EE463 and the final in EE464. Major milestones include the project report v2 due the end of EE460, the interim report at the end of EE463, and final submission at the conclusion of EE464. No work is scheduled during summer break, but liable to change depending on the progress achieved during EE463.

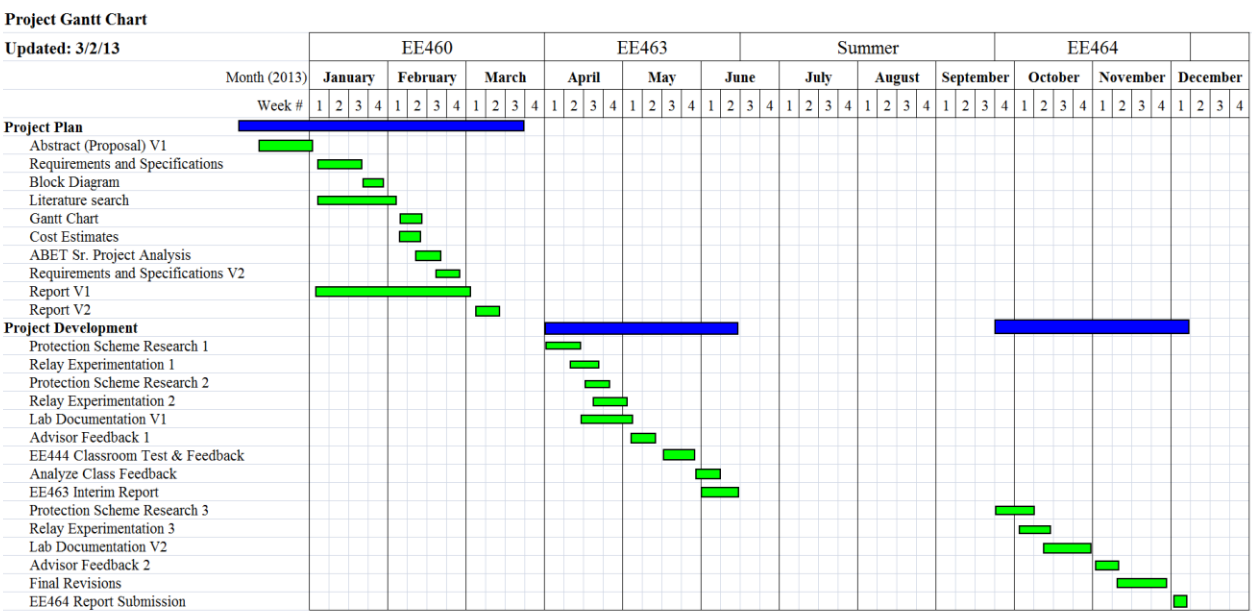

Figure 19: Initial project schedule

The actual timeline for the project is shown in Figure 20. Additional time was required for breaker and fault box research, seeking the equipment donation, prototyping, fabrication, and assembly.

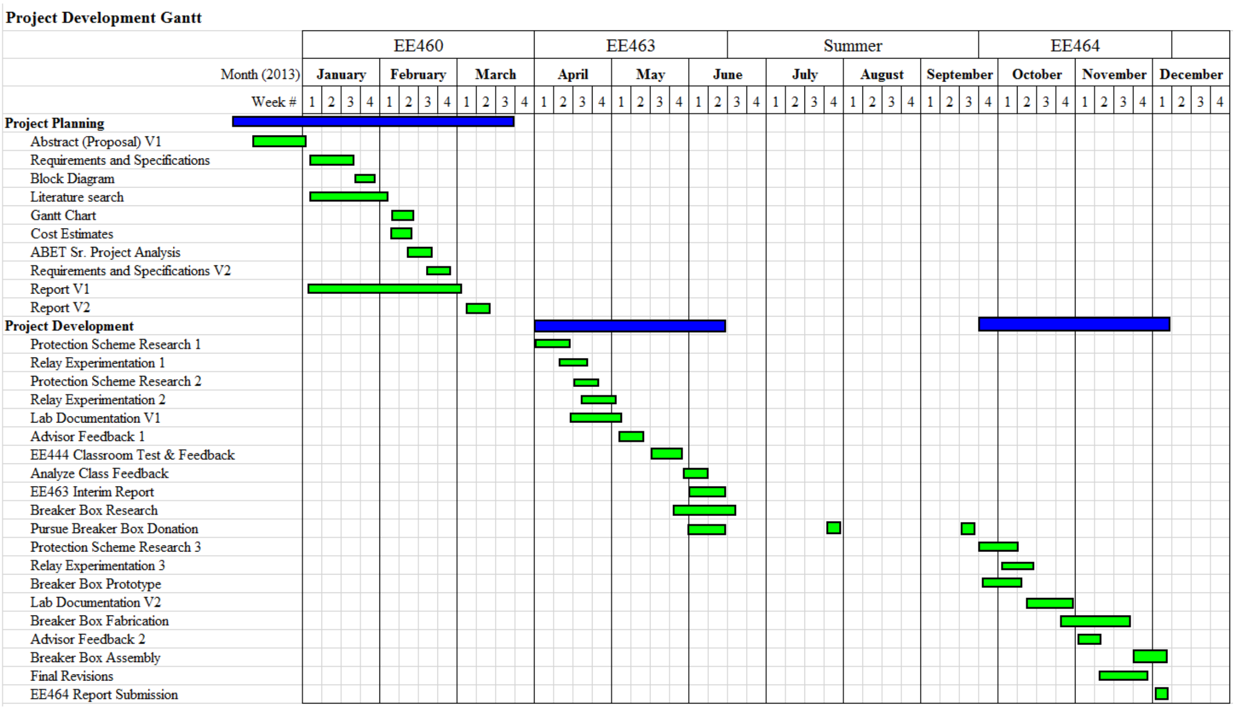

Figure 20: Actual project schedule

APPENDIX D – PROJECT ANALYSIS

Project Title: Motor Protection Lab Experiment using SEL-710

Student's Name: Ozro Corulli

Student's Signature:

Advisor's Name: Dr. Shaban

Advisor's Initials &Date:

1. Summary of Functional Requirements

See Table 1, Lab Experiment Requirements and Specifications.

2. 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?

This project develops a lab experiment for donated equipment, no prior classroom instruction has been given regarding the usage of these devices making the majority of the project self-learned. Constrained access to equipment for development by University property policy and high voltage lab procedures requiring a second person present at all times. Project limiting factors consist of available lab equipment and available laboratory time for the students.

What made your project difficult? What parameters or specifications limited your options or directed your approach?

I ran into difficulties scheduling time to use Cal Poly's laser printer to construct the breaker and fault boxes due to a two week waiting period. The size of the breaker and fault box had to be reduced from the original design to fit in the project boxes owned by Cal Poly's EE department.

3. Economic

• What economic impacts result? Consider:
Human Capital – What people do.
Financial Capital – Monetary instruments.
Manufactured or Real Capital – Made by people and their tools.
Natural Capital – The Earth's resources and bio-capacity.

This project's economic impact includes a potential human capital increase in the field of protection engineering as more students are introduced to the field. Experiment adoption by Universities requires a capital investment of $3,564 per bench in equipment if not already owned,

see Appendix B for cost analysis details. The project's natural capital depends upon the number of benches equipped.

• Timing - When and where do costs and benefits accrue throughout the project's lifecycle? When do products emerge? How long do products exist? What maintenance or operation costs exist?

Classroom implementation requires a large initial capital investment, ongoing costs consist of standard university lab upkeep including instructor salary and equipment maintenance. Financial benefits to the university may include increased power systems grants and/or donations as students move into the work place.

Upon project completion in December 2013, the experiment will integrate into the next EE444 class in Spring 2014. The learning objectives from this lab remain relevant for decades as SEL is a widely used product in the power protection industry. Ongoing costs consist of standard university lab upkeep including instructor salary and equipment maintenance.

• What inputs does the experiment require? How much does the project cost? Who pays?

See Appendix B for cost estimate.

Actual final cost of component parts (at the end of your project)

See Appendix B for final cost.

Attach a final bill of materials for all components.

See Appendix B for the bill of materials.

• How much does the project earn? Who profits?

The project produces no direct financial profit but does improve the University's educational standing resulting in possible grants and donations.

•Original estimated development time:

See initial project schedule, Figure 19 in Appendix C.

•Actual development time:

See actual project schedule, Figure 20 in Appendix C.

4. If manufactured on a commercial basis:
• Estimated number of devices sold per year

If sold on a commercial basis, an estimated sale to 10 universities the first year.

• Estimated manufacturing cost for each device

To implement the new experiment, the lab instructor would need time to become familiar with the lab. The manufacturing cost for SEL equipment is not available.

• Estimated purchase price for each device

The single lab experiment would be sold on a licensing basis to the University for $250, the equipment for an additional $3,564 per lab bench.

• Estimated profit per year

At an estimated 10 licenses sold the first year, an approximant profit of $2500.

• Estimated cost for user to operate device, per unit time (specify time interval)

Ongoing costs consist of standard university lab upkeep including instructor salary and equipment maintenance. Over a one year time period, one 3 hour lab period would cost ~$200 assuming the teacher makes $100k a year, including benefits, works 40 hours a week at 35 weeks a year.

5. Environmental
• Describe any environmental impacts associated with manufacturing or use, explain where they occur and quantify.

The manufacturing of the breaker and fault boxes requires metal and plastic production. Student lab manuals contain ~10 pages per experiment, however, this lab replaces an existing lab resulting in no additional environmental impact. The lab experiment requires a power usage in the range of 1kW per bench. The environmental impact of SEL relay production is not available, but electronic devices usually contain hazardous materials including lead, barium, and cadmium.

• Which natural resources and ecosystem services does the project use directly and indirectly?

During experimentation, each bench requires power in the kWh range. Natural resources expended during power generation can include the burning of natural gas, generation of nuclear waste, and disruption of fish ecosystems near hydroelectric facilities.

• Which natural resources and ecosystem services does the project improve or harm?

This project indirectly harms the ecosystems affected by power generation including fish and bird habitats.

6. Manufacturability

•Describe any issues or challenges associated with manufacturing.

Manufacturing the breaker and fault boxes requires the use of a laser etcher. The current student lab manual needs updating with new experiment documentation. Distributing to other Universities by email causes no challenges, ordering additional equipment may take several weeks and require capital investment, see Appendix A for cost analysis.

7. Sustainability

• Describe any issues or challenges associated with maintaining the completed device, or system.

SEL equipment needs calibration and upkeep similar to other lab equipment, keeping the lab curriculum up to date depends on updates from SEL.

• Describe how the project impacts the sustainable use of resources.

This project teaches power protection concepts designed to reduce equipment damage, resulting in a reduction of resources required to replace existing machinery.

• Describe any upgrades that would improve the design of the project.

Adding additional protection schemes would introduce students to more protection concepts, perhaps the addition of synchronous machine protection.

• Describe any issues or challenges associated with upgrading the design.

Additional protection schemes would require more time, possibly exceeding the 2 hour and 50 minute lab time frame.

8. Ethical

•Describe ethical implications relating to the design, manufacture, use, or misuse of the project. Analyze using one or more ethical frameworks in addition to the IEEE Code of Ethics.

Ethically bound by a rule of virtue, Cal Poly must fulfill expectations placed upon them in each of the following cases:

- To the student: Student's expect to learn about and gain firsthand experience with protection relaying when taking this class.

- To the donors: Schweitzer Engineering Laboratories and Schneider Electric donated the equipment with the understanding Cal Poly would create a power protection lab.
- To the industry: Cal Poly has an ethical obligation to produce graduates proficient in their area of study.

In fulfilling each of these expectations, Cal Poly reinforces their commitment to excellence and integrity, this project helps Cal Poly meet these expectations. Upon completion, the lab introduces students to the donated SEL equipment, giving them hands on experience and increasing their proficiency once in the field. According to the IEEE code of ethics, an engineer must "maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations." Cal Poly graduates working in the power industry hold public trust to keep the lights on and power following. Equipping students with hands on experience and a firm understanding reduces the risk of mistakes once in the field.

9. Health and Safety

•Describe any health and safety concerns associated with design, manufacture or use of the project.

This project contains safety concerns due to high voltage use [3]. The project uses three phase 208V and must be handled with care, improper use can result in injury or death. Always follow Cal Poly lab guidelines while working with high voltage.

10. Social and Political

• Describe social and political issues associated with design, manufacture, and use.

This project educates Cal Poly students in the latest power protection equipment, giving them valuable hands on experience. This experience further elevates Cal Poly's reputation as a leading engineering University.

• Who does the project impact? Who are the direct and indirect stakeholders?

Direct stakeholders in this project include Cal Poly EE staff, students, and Schweitzer Engineering Laboratories. Indirect stakeholders include electricity customers and companies who hire Cal Poly students.

• How does the project benefit or harm various stakeholders?

Cal Poly students gain firsthand experience working with the latest power protection equipment. Schweitzer Engineering Laboratories gains a larger customer base familiar with their product. Electric customers gain a power system with greater reliability, and electric companies gain employees with hands on experience.

• To what extent do stakeholders benefit equally? Pay equally? Does the project create any inequities?

The Cal Poly students benefit the most from this project with hands on experience making them more marketable. This project replaces a current power systems lab experiment, reducing the experience students have with the replaced subject.

11. Development

•Describe any new tools or techniques, used for either development or analysis that you learned independently during the course of your project.

The majority of knowledge used to create this project is independent of classroom instruction, learned during summer internships. Self-taught techniques include relay setup, relay programming, and protection schemes. The lack of relay instruction is one of the key reasons for this project. During the project, I also learned about the following techniques: using a laser etcher, donation soliciting, motor contactors and their power ratings.