# Power Distribution: Protection Analysis

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## Abstract

The objective of this project is to build a radial distribution system that operates on a lower voltage. The system consists of a transmission line protected by a SEL-351 Relay, a three-phase transformer protected by a SEL-587 Relay, and a three-phase induction motor protected by a Cooper Form 6 Controller. The SEL-351, SEL-587, and the Cooper Form 6 Controller are microprocessor-based relays that are used to provide protection under faulted conditions. When a fault is detected in the system, the closest upstream relay sends a trip signal to its assigned local breaker. The SEL-351 provides overcurrent protection for the transmission line and the Form 6 Controller provides overcurrent protection for the motor. The SEL-587 protects the transformer by using a current differential protection scheme. The testing involves faulting different locations on the system to analyze each protective relay with its designated protective zone. When the fault was applied to each zone, the responsible relay tripped based on its settings, which verified that the design worked. The benefits of this project are familiarization with protection schemes, the efficient operation of protective equipment and programming different microprocessor-based relays.

# Acknowledgments

I would like to thank everyone that took part in helping make this project a success.

**Professor Shaban:** Thank you for accepting to be my mentor for my senior project and being able to have input on how to accomplish the goals of my project.

**James Tuccillo:** Thank you for helping with the design aspect of the project. In addition, all Pacific Gas and Electric contributions made the project cost effective.

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# I. Introduction/Background

Electric Utility Companies provide electricity to their customers through different generation methods: turbines, solar, wind, etc. [13]. The power system grid splits into three different levels: transmission, sub-transmission, and distribution. The transmission level operates on high voltages above 60 kV [14]. The distribution side, on the other hand, operates on lower voltages of 21 kV and under [14]. A distribution system provides power to industrial loads, homes, and businesses. The system is built with a stable and reliable protection scheme to safeguard the equipment and customers. In order to maximize safety, the systems ability to control power to the malfunctioning equipment is crucial. Controlling the power to a faulted scenario is highly dependent on relay tripping and coordination – making sure the closest upstream breaker opens to clear the fault. The ultimate goal is to de-energize the faulted part of the system, while maintaining power to the rest of the system.

The radial distribution system built in this project uses different relays to protect the transmission line, three-phase transformer, and the three-phase induction motor. The SEL-351, SEL-587, and the Cooper Form 6 Controller are responsible for the protection of their own protective zones. Each relay is programmed with settings that allow for timed tripping in relation to the location of the fault. As the faults occur closer to the source, the fault currents increase in magnitude, due to the lower impedance [3]. Figure 1 below shows an example of inverse time curves for protective devices. Based on the relays chosen, the curves can be adjusted to change the trip speed of the breaker. If an overcurrent appears on the line, the relay picks-up on the fault and trips the local breaker based on the relay settings [10].

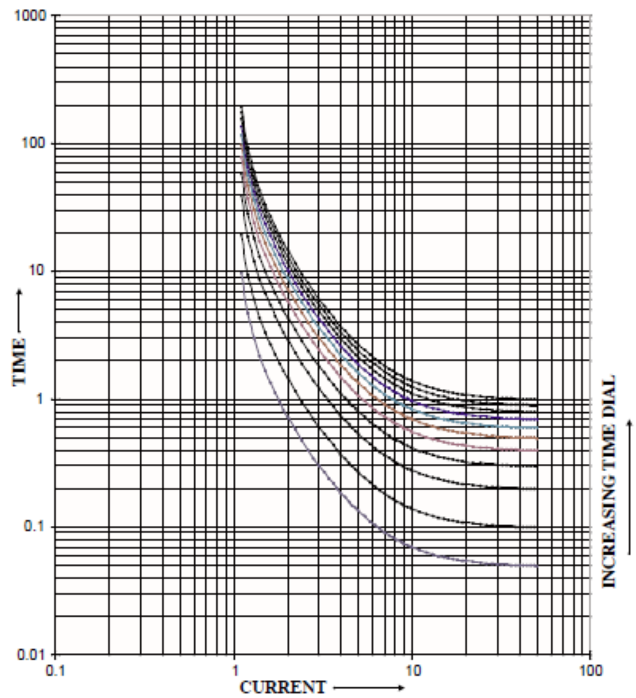


**Figure 1: Relay Coordination Curves [9]**

The system uses two types of relays: overcurrent and differential [1][5][6]. The first overcurrent relay (SEL 351) protects the first portion of the line, the differential relay (SEL 587) protects the transformer, and the second overcurrent relay (Form 6-LS Relay) protects the motor. A current difference between the measured primary and secondary side of the transformer allows the SEL-587 relay to send a trip signal to the local breaker. Any overcurrent faults outside SEL-587 zone will trip the SEL-351 or the Form 6 Controller depending on the location of the fault. The design consists of resistive and inductive elements to match an actual transmission line, which is protected through the SEL-351. The Form 6 Controller protects the 3-phase induction motor load. The zone protection scheme provides the system with full protection to prevent any damages to the equipment when a fault is applied to the system.

## II. Requirements and Specifications

The objective of the project is to build a radial power system with full protection. Working for Pacific Gas & Electric has enhanced my knowledge about the operation of power systems, which certified my skills to operate the protective equipment and create a functioning distribution system design [14]. The power system courses at Cal Poly helped develop the first phase of the project, which was designing the system. Table 1 below shows all the necessary specifications and requirements needed to construct the project in a safe manner. Each specification validates a major component of the design to address the ACME requirements [15].

**Table 1: Requirements and Specifications**

| Marketing Requirements | Engineering Specifications | Justification |
|---|---|---|
| 2,3,5,7 | All equipment operates on a 240 AC voltage. | The Cal Poly lab stations operate at 120/240 V. Experiment uses a three-phase 240V source. |
| 2,6 | Protection relay timing coordinates with fault location. Device closest to the fault from the source side trips first [4]. | Protective device have the ability to sectionalize a portion of the line to allow some customers with power. |
| 5,6 | Experiment includes four fault points, which take on LL and LLL faults. | Development of different fault duties allows for understanding how sequence parameters work hand in hand with overcurrent conditions on the system. |
| 3,8 | System operates radially – current only flows in one direction [8]. | Some distribution lines have generation from external customers, which can provide a back feed. This experiment only deals with one generating source that feeds one way. |
| 5 | Transformer input and output current difference is less than .5%. | Internal magnetizing current that could force false differential tripping. |
| 1,3 | Transformer operates in a delta-delta configuration. | The high and low side of the transformer are both delta connected to account for line loses and produce a 208V Line to Line on the secondary. |
| 3,5 | System includes three protective relays, which operate the breakers. Two relays operate as an overcurrent relay and the other operates as a differential relay [14][2]. | These devices provide protection to the system equipment. Each device has a designated zone to protect under normal and faulted conditions. Each relay is attached to a local breaker. |

<table>
<tr><td>3,5</td><td>Protective devices trip within three seconds from when the fault occurs as back up [9].</td><td>When a fault occurs on the line, its necessary to clear the fault before equipment gets damaged.</td></tr>
<tr><td>1,2,3,4,7</td><td>Load constructed with three-phase induction motor.</td><td>Operating current can’t go beyond 2A due line voltage drop. Motor needs 208V to operate. Additional loads would increase current input, which results in more voltage drop on the line.</td></tr>
<tr><td colspan="3">Marketing Requirements<br>1. Low Power Circuit using 240V<br>2. Safety Protocols<br>3. Easy Measurements<br>4. Equipment Protection<br>5. Multiple Fault Points<br>6. No external generation<br>7. System operates on 60Hz<br>8. Radial System</td></tr>
</table>

## III. Planning

The expected time frame for designing the project, gathering the material, and building was six weeks; however, it nearly doubled due to design complications. The Gantt chart below shows the expected completion of every task throughout my project. The first and only build cycle was implemented within the first 3 weeks of EE 462 – build cycle 2 was not necessary. All the testing and retrieval of data was completed towards the eighth week of EE 462. Having all the relay settings completed and a functioning design schematic draw out before starting EE 462 was very beneficial. The estimated completion hours for the whole project were about 160 hours.

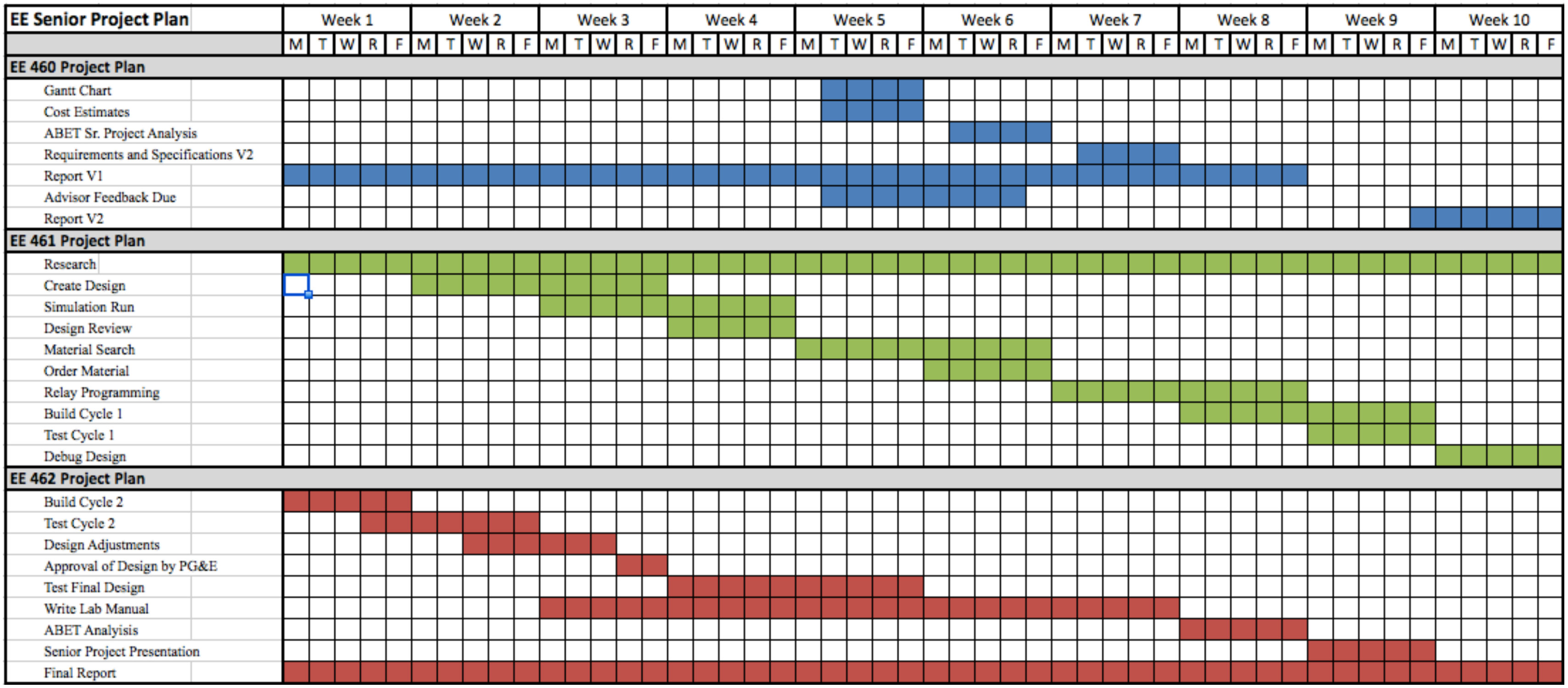


**Figure 2: Gantt Chart**

## IV. Design

This portion of the project includes all the design details for building the distribution system. Figure 3 and Table 2 show the inputs and outputs for the overall system and explain the basic functionality. Figure 4 and Table 3 go into an in-depth internal view of the block 0 diagram in Figure 3. The block diagrams below helped create the basic structure for this project. Table 3 explains each portion of the model to provide a purpose for the design.

**Table 2: Function Table for High Level Block Diagram**

| Module | Power Distribution Model |
|---|---|
| Inputs | 240 AC Voltage – The line powered through this source. |
| | Faults – Four locations on the system were faulted to test protection scheme. |
| | |
| Output | Measurements – Overcurrent measurements from the downloaded relay plots. |
| Functionality | Power the system and introduce faults at the busses that are visually seen through the functional protection scheme – reviewable plots generated per phase. |


**Figure 3: High Level Block Diagram**

**Table 3: Function Table for Low Level Block Diagram**

| Module Internals | Details |
|---|---|
| 240 AC Voltage | The line powered through this source. |
| SEL 351/CB | Overcurrent relay that detects overcurrent in the line and trips the breaker to clear the fault. Protects the whole line from damages [5][10]. |
| Resistor/Inductor | Represent the transmission line impendences. |
| SEL 587/CB | Differential relay that detects the difference of current across the transformer and trips breaker if current exceeds set limit. Protects the transformer and loads from damages [6][10]. |
| Transformer | Converts the 240 V to 240 V, which allows the induction motor to operate accounting for line loss. |
| Recloser/CB/CT | Relay uses the overcurrent technique to protect the loading of the system by sending a signal to the breaker to open. The controller itself can only take an incoming signal of 1A – the CT is used to lower the current of the overall system. |
| 3-Phase Induction Motor | The maximum load before the available voltage is to low due to line voltage drop. |
| 1-3 Buses | Connection points between line equipment [7]. |

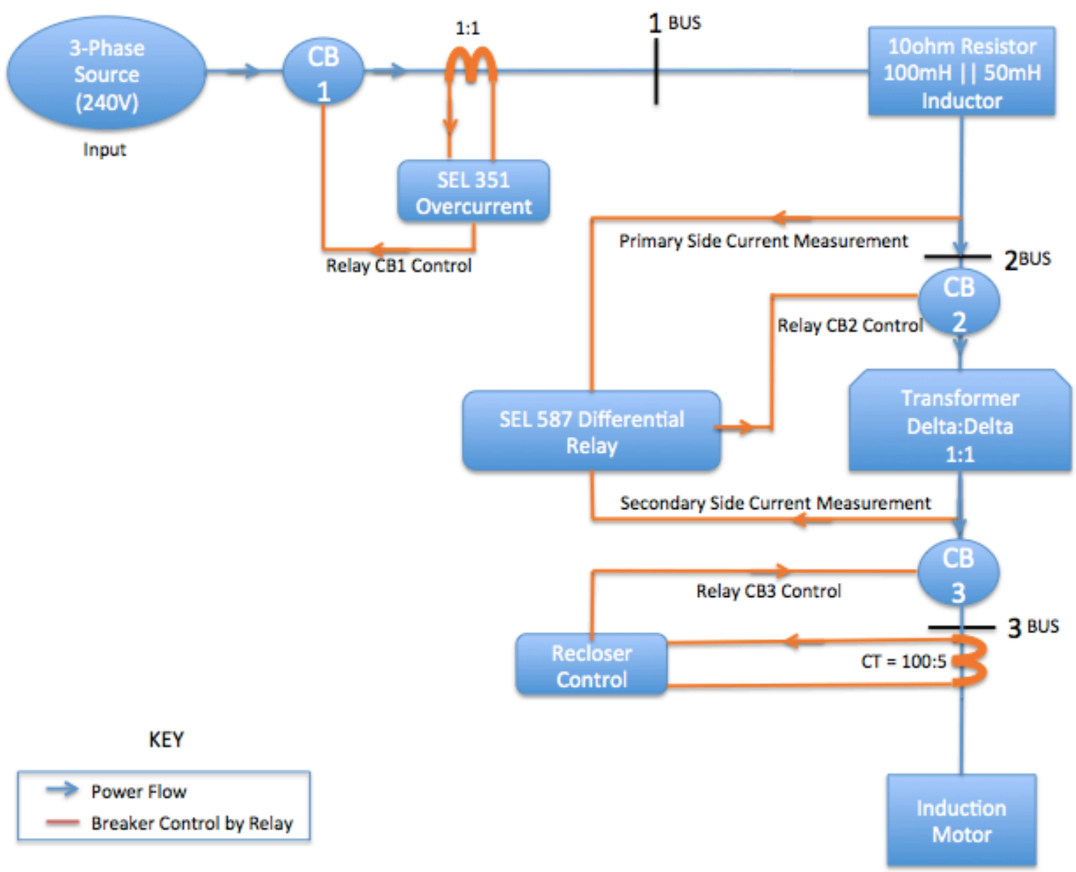


**Figure 4: Overall System Design**

## 1. Line Protection by SEL 351

The SEL-351 relay is an overcurrent relay, which protects the transmission line. Refer to the transmission line section below for more details. This relay is programmed to trip if it picks-up a current exceeding the 51PP settings. Once the fault conditions are met, the relay will send a trip signal to command the breaker to open – refer to the breakers section below for the type of breaker used and Appendix A for the relay settings.

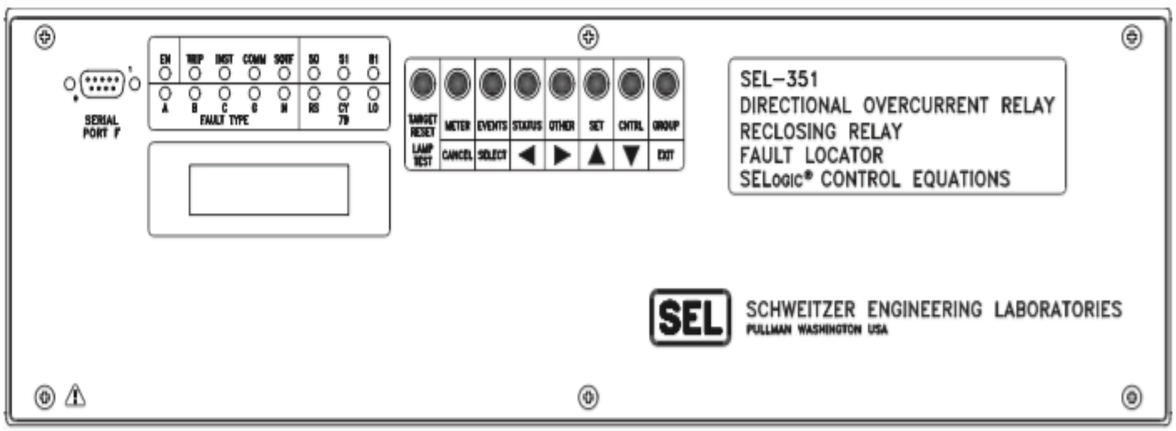


**Figure 5: SEL 351x1 Front Panel**

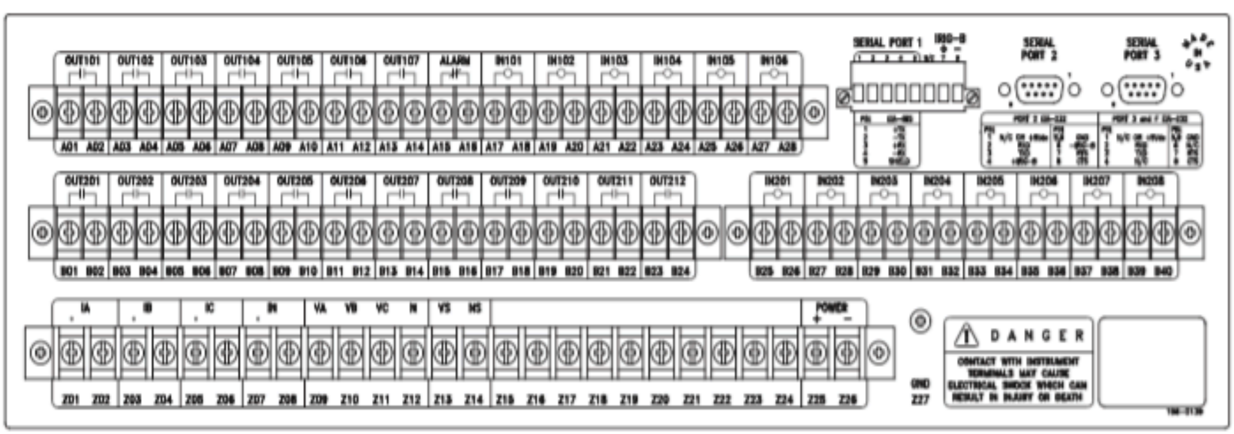


**Figure 6: SEL 351x1 Back Panel**

Most relays require a current transformer connection to lower the current from the primary side to an allowable current on the secondary side of the relay. In this case, the currents used in this project don't exceed 2A and the relay itself has a nominal operating current of 5A – allowing direct input/output connections from the system to the relay as shown in Table 4. The polarity of the trip signal doesn't matter when connecting the relay to the breaker, but the trip signal in the settings should be inverted, since the connection is made from a normally open relay to a normally closed breaker.

**Table 4: SEL 351 to Circuit Connections**

| Signal Operation | SEL 351 Connection | Circuit Connection |
|---|---|---|
| A Current In | 201 | CB 1 A Out |
| A Current Out | 202 | A Line Impedance Connection (In) |
| B Current In | 203 | CB 1 B Out |
| B Current Out | 204 | B Line Impedance Connection (In) |
| C Current In | 205 | CB 1 C Out |
| C Current Out | 206 | C Line Impedance Connection (In) |
| Trip Breaker (+) | A01 | CB 1 Trip (+) |
| Trip Breaker (-) | A02 | CB 1 Trip (-) |

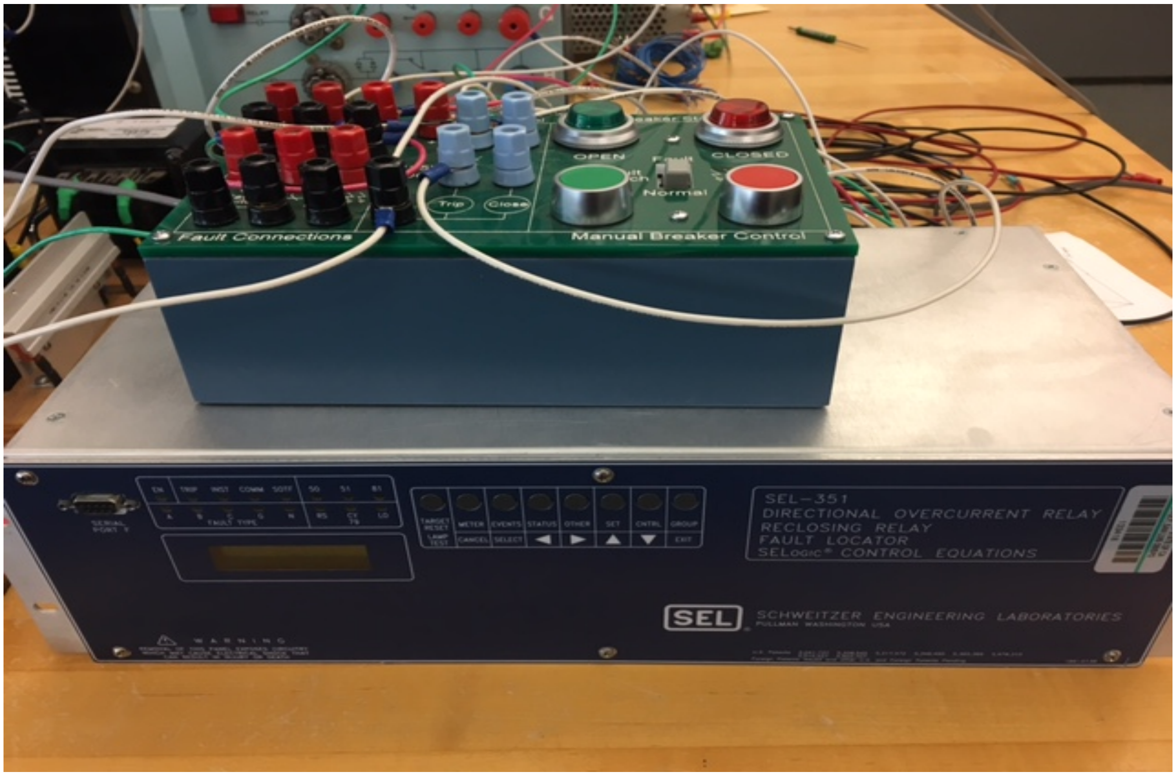


**Figure 7: SEL 351 and Breaker Set-Up**

## 2. Transformer Protection by SEL 587

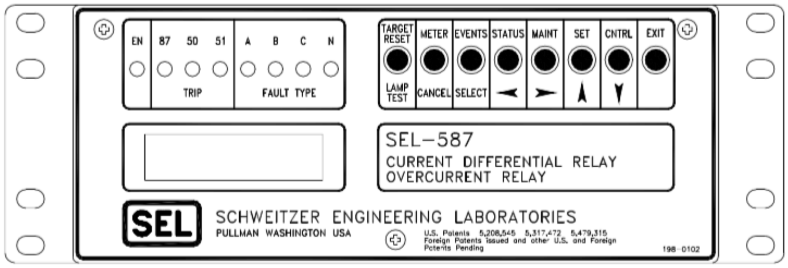


**Figure 8: SEL 587 Front Panel**

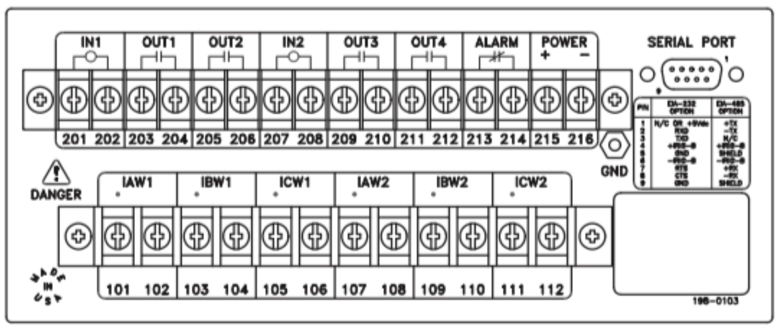


**Figure 9: SEL 587 Front Panel**

The SEL-587 relay front and back panels are shown in Figures 8 and 9 above. The SEL-587 is a differential protection relay used to provide differential current protection for the transformer. The current differential protection is used to catch any faults or anomalies between the primary and secondary windings of the transformer – the input current has to be equivalent to the output current assuming it's an ideal transformer. If the relay senses an unbalanced winding current differential in any phase, it will send a trip signal to the breaker. The connections from the relay to the circuit are shown in Table 6 below. The trip signals connected between the relay and breaker are not polarity sensitive, but the signal needs to be inverted in the settings since a normally open relay is connected to a normally closed breaker. The SEL 587 relay contains internal accountability for different transformer connections – Table 5 was used to accurately create settings for the design being used. The design for this project uses a delta-delta transformer as shown in Figure 10.

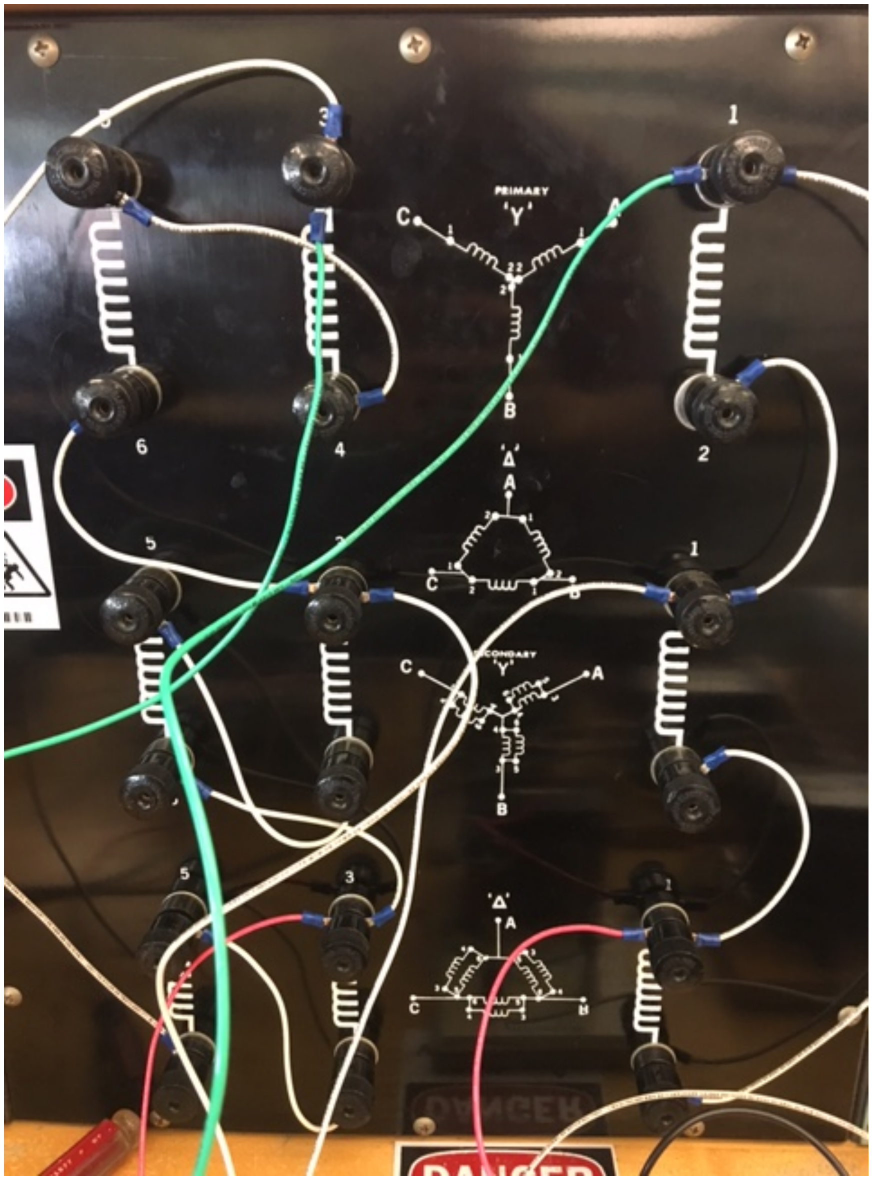


**Figure 10: Transformer Delta-Delta Connection**

In the initial design, a delta-wye transformer with a 2:1 ratio was being used. Alterations were made to the original design to allow for a reasonable voltage at the end of the line to meet motor specifications – a 1:1 transformer ratio was used by putting two secondary windings on the panel in series to get a 240V:240V transformer. Within the settings for the relay, the value of TRCON = DACDAC and CTCON = YY. In this project, the TAPs were automatically calculated using the values provided for MVA, $V_{LL}$, and CT Ratio.

**Table 5: SEL 587 CT Connection Scheme**

| TRCON | CTCON | CON1 | CON2 | C1 | C2 |
|---|---|---|---|---|---|
| YY | DACDAC | Y | Y | $\sqrt{3}$ | $\sqrt{3}$ |
| YY | DABDAB | Y | Y | $\sqrt{3}$ | $\sqrt{3}$ |
| YDAC | DACY | Y | Y | $\sqrt{3}$ | 1 |
| YDAB | DABY | Y | Y | $\sqrt{3}$ | 1 |
| DACDAC | YY | Y | Y | 1 | 1 |
| DABDAB | YY | Y | Y | 1 | 1 |
| DABY | YDAB | Y | Y | 1 | $\sqrt{3}$ |
| DACY | YDAC | Y | Y | 1 | $\sqrt{3}$ |
| YY | YY | DAB | DAB | 1 | 1 |
| YDAC | YY | DAC | Y | 1 | 1 |
| YDAB | YY | DAB | Y | 1 | 1 |

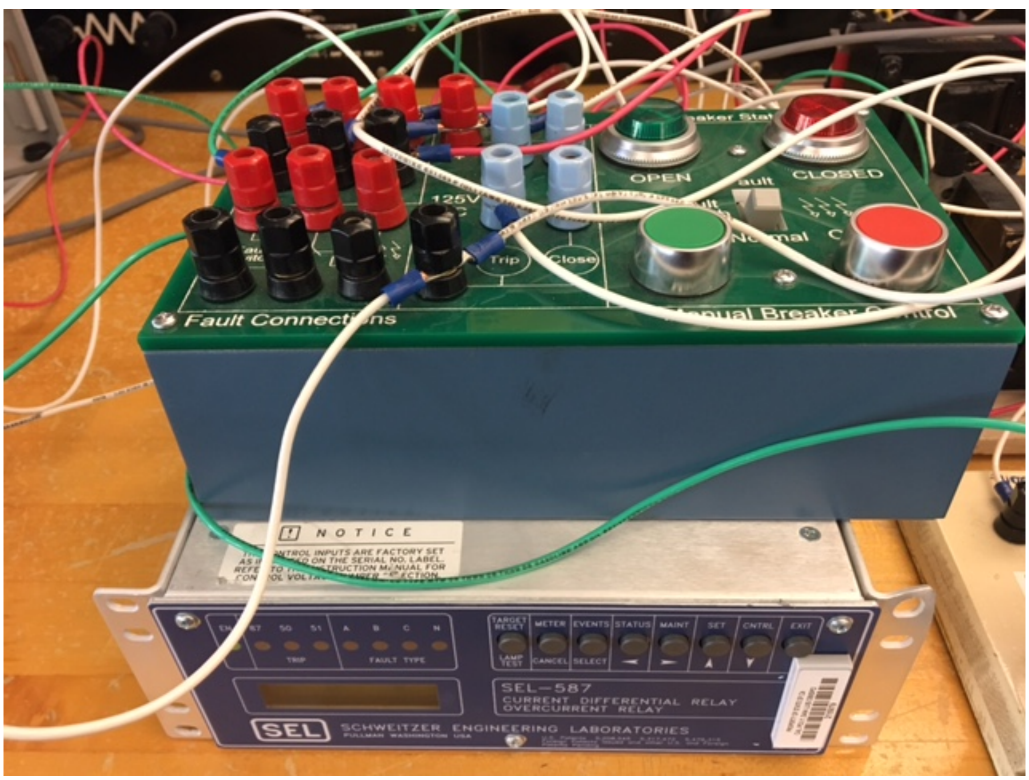


**Figure 11: SEL 587 and Breaker Set-Up**

**Table 6: SEL 587 Circuit Connections**

| Signal Operation | SEL 587 Connection | Circuit Connection |
|---|---|---|
| Primary A Current In | 101 | Line Impedance A (Out) |
| Primary A Current Out | 102 | CB 2 A In |
| Secondary A Current In | 108 | Transformer A Out |
| Secondary A Current Out | 107 | CB 3 A In |
| Primary B Current In | 103 | Line Impedance B (Out) |
| Primary B Current Out | 104 | CB 2 B In |
| Secondary B Current In | 110 | Transformer B Out |
| Secondary B Current Out | 109 | CB 3 B In |
| Primary C Current In | 105 | Line Impedance C (Out) |
| Primary C Current Out | 106 | CB 2 C In |
| Secondary C Current In | 112 | Transformer C Out |
| Secondary C Current Out | 111 | CB 3 C In |
| Trip Breaker (+) | 203 | CB 2 Trip (+) |
| Trip Breaker (-) | 204 | CB 2 Trip (-) |

The connections shown in Table 6 were adjusted to conform to the project design. In differential relays, the IOP value should be close to zero, since the primary and secondary currents through the operating coil are 180 degrees out of phase. The issue arose when the secondary current measured by the relay didn’t cancel out with the primary. After investigation, it was found that without using a CT, the phase shift of 180 degrees isn’t applied. In order to compensate for the shift, the secondary side terminals were flipped on the relay.

# 3. Load Protection by Form 6 Controller

The Cooper Form 6 Controller shown in Figures 12 and13 is used to act like an overcurrent relay. If the motor starts to draw high current due to a faulted condition, the controller will trip the breaker. Any fault beyond the relay should be accounted for in coordination with the other upstream devices.

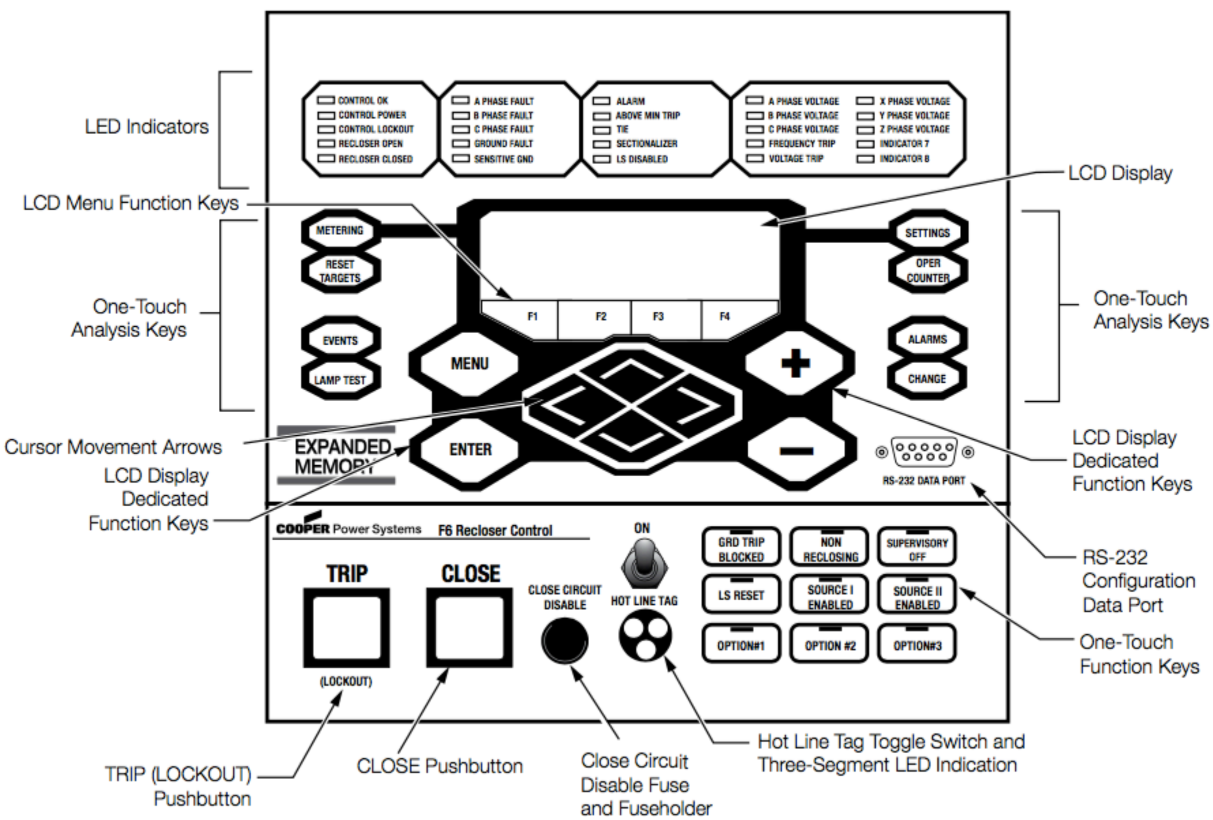


**Figure 12: Recloser Controller Front Panel**

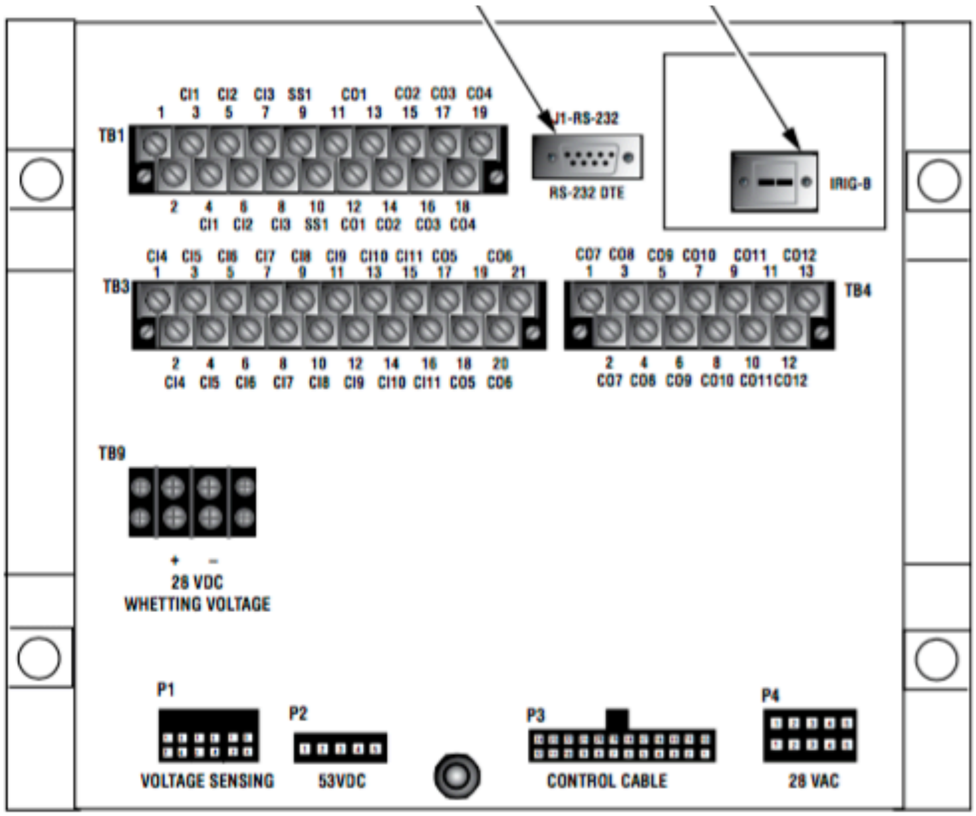


**Figure 13: Recloser Control Unit Back Panel**

Due to the complexity of the controller, the whole unit had to be powered up by the power supply board provided by PG&E. The power board connects to the P4 contact shown in Figure 13, which powers the controller. The ports on the controller have many different uses, but the main contacts used for the project are TB1 and P3. The pin layouts are shown in Figures 14 and 15 and Table 7. Contact P3 allows the controller to measure the current on the line. In order to control the breaker, TB1 contact was programmed as an output trip signal.

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 24 | 23 | 22 | 21 | 20 | 19 | 18 | 17 | 16 | 15 | 14 | 13 |
| 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 |


**Figure 14: P3 Pin Numbering**

**Table 7: P3 Pin Descriptions**

| Pin Number | Description |
|---|---|
| 1 | VTC (28V Out) |
| 2 | Trip |
| 3 | Close |
| 17 | Phase A In Measurement |
| 18 | Phase B In Measurement |
| 19 | Phase C In Measurement |
| 20 | Neutral |

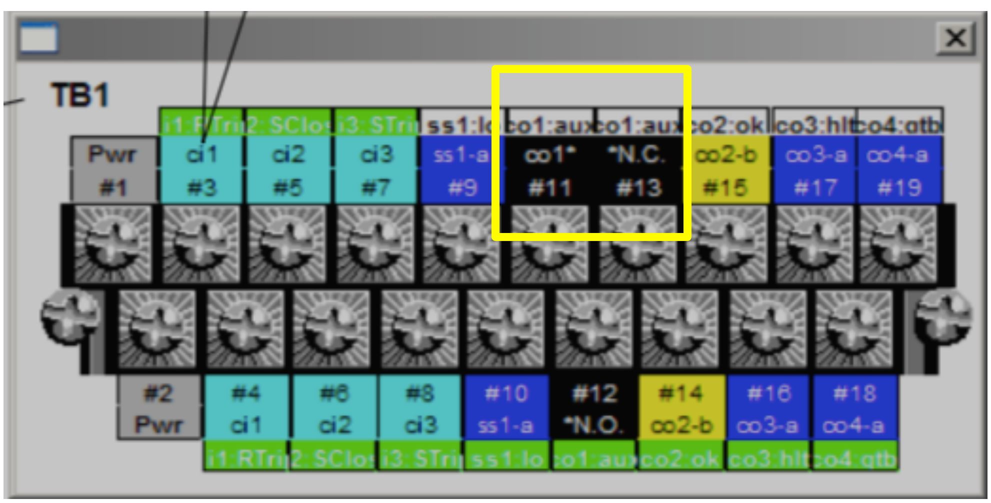


**Figure 15: TB1 Pin Numbering**

For measuring the currents, pins 17,18, and 19 on P3 are connected to the secondary side of the 100:5 CT in Y configuration. The primary side is connected between the output of CB3 and the motor for each phase. The controller requires a CT due the nominal operating current of 1A for the controller. The system runs a maximum of 1.6A under normal conditions to the motor, which will be dropped down by the CT factor as shown below. Due to the high voltage/current operation in utility, the controller setting doesn't allow for a 100:5 CT ratio setting – the minimum is 500:1. Having different CT factors, all readings are adjusted accordingly.

Actual CT Ratio: 100:5 (Lab doesn't contain a higher CT ratio)
Controller Setting CT Ratio: 500:1 (Use in Industry)
$I_{Secondary} = I_{relay} = I_{Primary}$ / Actual CT Ratio = 1.6A / (100:5) = 1.6A / 20 = .08A

The controller measures currents that are off by a factor of 25 from the primary due to the different CT ratios. The relay reads 40A going through the line, but the current on the line is still 1.6A – a factor of 25 is multiplied to the 1.6A. When preparing the settings, this factor increases the minimum to trip value by factor of 25.

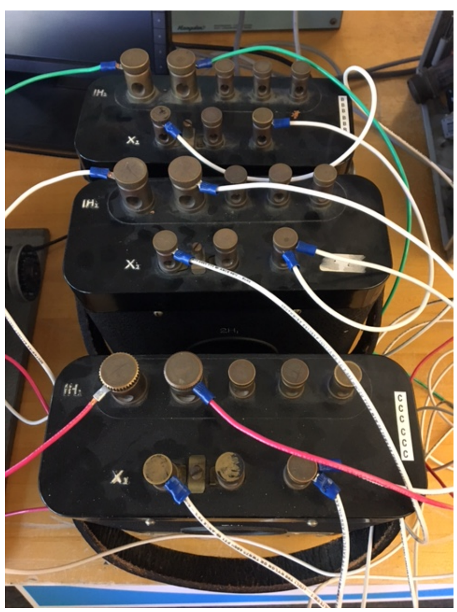

**Figure 16: CT Connections for Form 6 Controller**

In industry, pins 1,2,and 3 from Table 7 are used to control the breaker, but these pins do not work with an external breaker. The controller has built-in output ports on the TB1 contact shown in Figure 15 that are programmable to trip the breaker. Using Proview 4.0 Software, the output pins 11 & 13 (CO1 – Normally Closed) are programmed to trip the breaker. The control trip/close capability is disabled since pins 1-3 are not used. This becomes an issue when the power of the system is turned on, but the controller believes there is no trip/close functionality connected so it trips the breaker through an internal trip failure alarm. The trip failure alarm can be bypassed by adding a short across the trip coil of the breaker before the system starts running. Once the power is turned on to the system, the alarms are reset from the front panel. Once the controller has reset, the short across the trip terminal of the breaker can be removed for normal operation of the Form 6 controller and breaker.

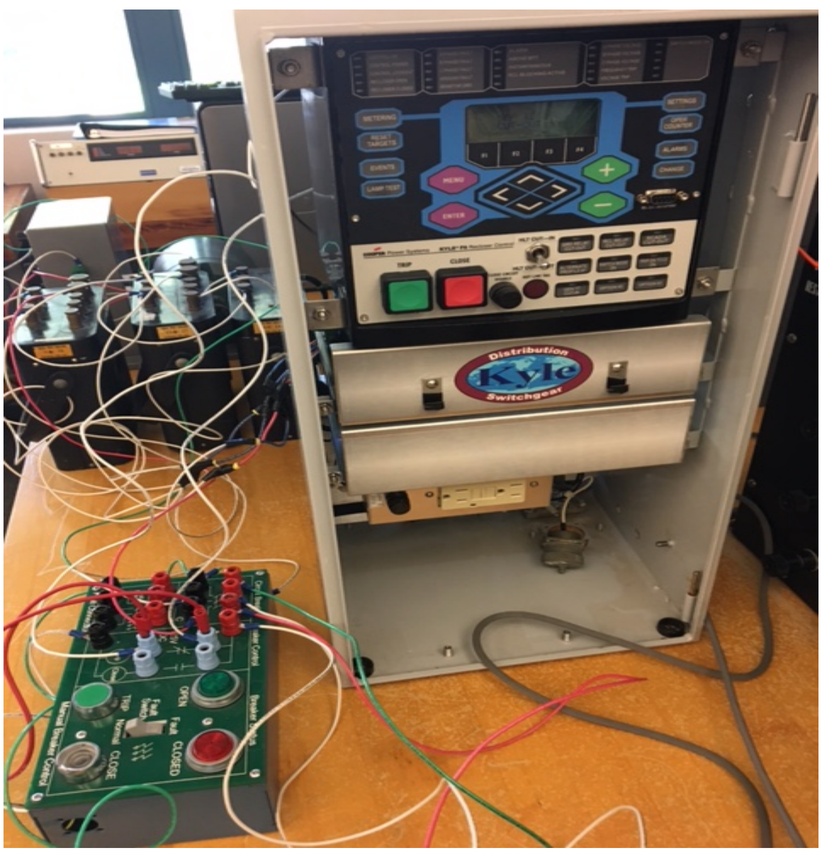


**Figure 17: Form 6 Unit and Breaker Set-Up**

## 4. Breakers

The circuit breakers used for this project were constructed by a former Cal Poly student [17]. The unit has a switch for Normal and Fault operations. In each case, three input and three output terminals are provided, which have an internal closed switch position until the breaker receives a relay signal to trip. The breaker has two terminals for the close signal and two terminals for the trip signal. The inverted signal from the relay connects to the trip terminals on the circuit breaker. The unit itself operates on a DC voltage of 125V from an external source. The project focuses on line-line and three-phase faults at four different locations. A line-line fault can be created using the breaker by shorting two phases of the output terminals (black) on the fault switch section and connecting the output terminals of normal switch section to the input terminals (red) on the fault switch section, while the power is off and fault/normal switch is towards normal. Once the connections are made, turn on the power and flip the fault/normal switch to the fault position, which then introduces a line-line fault. Refer to Figure 18 below for circuit breaker connections.

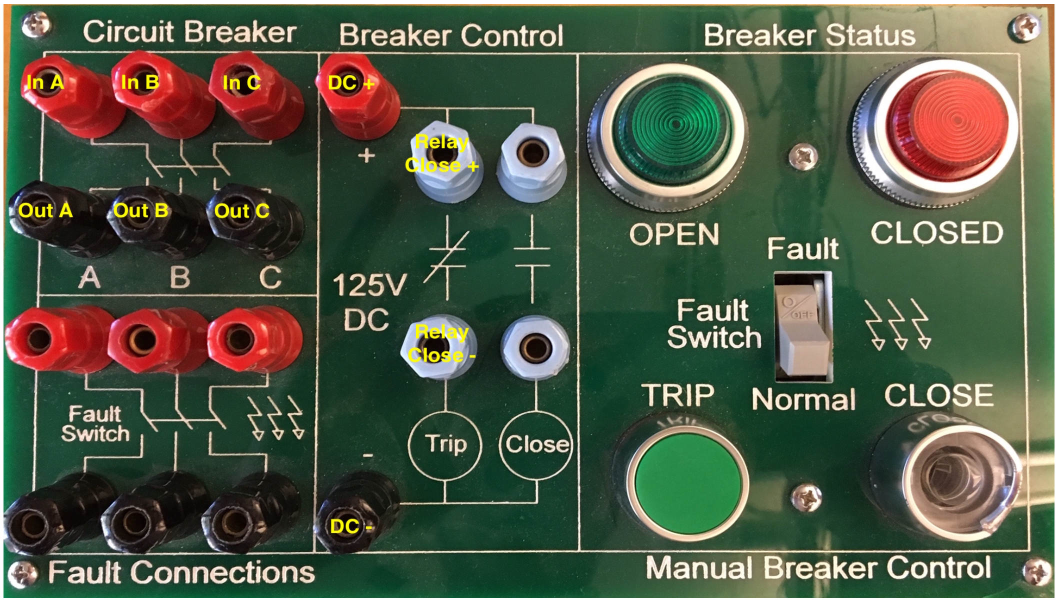


**Figure 18: Circuit Breaker Connections [17]**

## 5. Transmission Line

The transmission line is modeled using a resistor and an inductor. As Figure 19 shows, the line is built using a 10Ω resistor and a 100mH and 40mH inductors in parallel to reduce line voltage drop. Each phase has a line impedance of 10+j10.8 Ω. Due this impedance, the line drop is close to 30V with a max current of 2A on each phase, which drops the input voltage from 240V to 190V at the terminals.

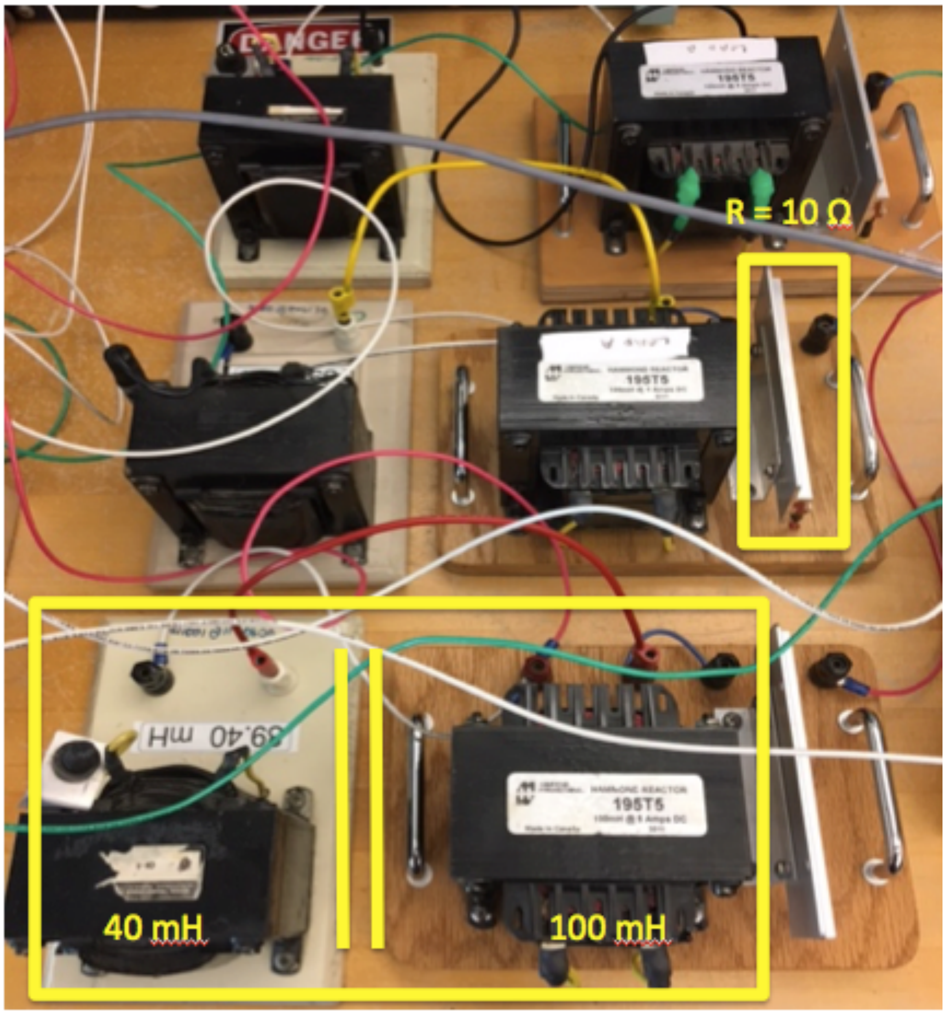


**Figure 19: Transmission Line (R with L||L)**

## V. Relay Tripping & Coordination

One of the main components of the project is the coordination between the SEL-351 and the Form 6 Controller. The differential relay does not come into the coordination scheme, since it has an instantaneous trip from the current differential scheme. Both overcurrent relays will trip on a time curve, which is set in the settings of the relay. Coordination is a concept, which allows for proper function of protection equipment based off the fault location. When a fault occurs on the line, the upstream devices closest to the fault should operate before any other devices operate.

As impedance increases down the line, the fault currents drop due to $I_F$=V/Z. In the project, the impedance throughout the system does not change drastically, so both relays are set at the same overcurrent trip value. Since the SEL 351 relay is closer to source compared to the Form 6 controller, the 351 uses a slower curve to operate on a fault condition – U5 curve with a 1 time dial had to be used to control faults under a certain time restraint. The controller uses a different time characteristics method – equations shown below for both relay methods.

**Time Curve Equations for SEL-351**

$tp = TD*(0.00262 + 0.00342/(M^{.02}-1))$

$tr = TD*(0.323/(1-M^2))$

TD = Time Dial

M = Multiples of Pickup

**Time Curve Equations for Form 6 Controller**

**Inverse Time Characteristics**

The ANSI and IEC Form 6 control curves are derived based on the following equations:

Trip Time:

$$T_t = TM \times \left(\frac{A}{M^P - 1} + B\right)$$

When Disk-like reset is selected for the ANSI curve shapes, the reset time is determined by the following formula:

$$T_r = TM \times \left(\frac{RCC}{M^2 - 1}\right)$$

Where:

M = Multiples of pickup

TM = Time multiplier setting

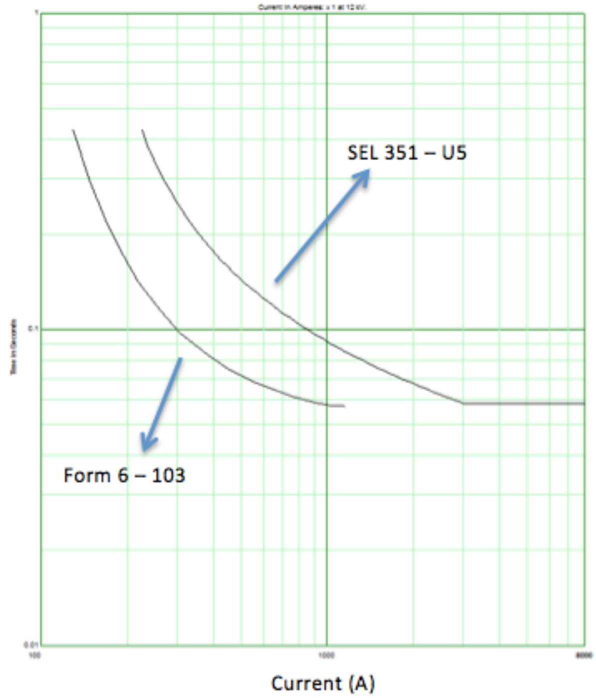


**Figure 20: Relay Coordination Curve**

The graph above in Figure 20 shows the U5 curve for SEL 351 and Kyle 103 curve for the Form 6 Controller. As the curves show, when the fault current is higher, the trip time on the y-axis is less. The least amount of impedance tends to be closest to the source, which means very large currents. The detailed settings for both devices are shown in Appendix A. The setting for the maximum current on the 351 is 5A, but due to the factor of 25 offset from the CT to Form 6 Controller, the curves use 130A as the minimum to trip current for coordination purposes. The SEL-587 current differential scheme is constructed using Figure 21 below. By adjusting the O87P, U87P, and the restraint slope in the SEL-587 settings, the primary and secondary side current differential can be tuned to the design parameters. Based on Figure 21 below, the differential will trip if the set U87P value is exceeded or if the IOP does not stay within the operating region.

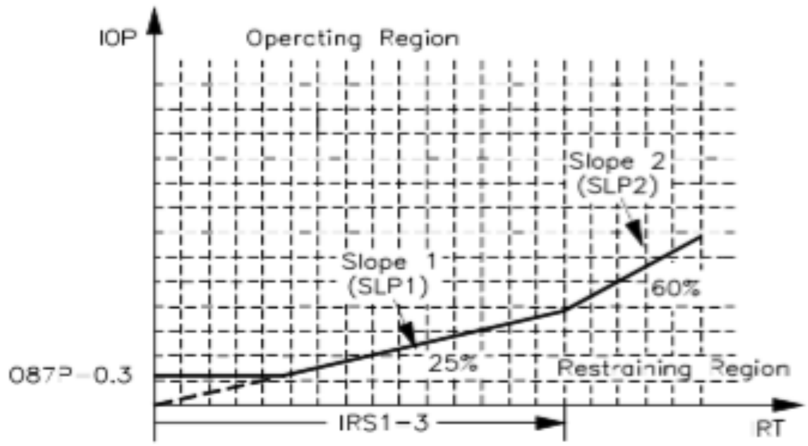


**Figure 21: SEL 587 Trip Curve**

The O87P value can be adjusted if the sensitivity is too high, which prevents false tripping from high magnetization current. Full settings for SEL 587 are shown in Appendix A.

## VI. Programming Software

**Table 8: Relay Password Entrance**

| Relay | Level 1 Password | Level 2 Password |
|---|---|---|
| SEL 351 - 1 | OTTER | TAIL |
| SEL 587 - 1 | 587 | 587 |
| NOVA Form 6 - LS | Modify | -- |

The two main software programs used to complete the programming on the relays are SEL's Acselerator Quickset and Proview 4.0. SEL 351 and 587 relays used the quickset software, while the Form 6 Controller used Proview 4.0. The connection between the computer and the SEL relays was using an EIA 232 cable provided in lab, while the Cooper controller was connected using a R232 cable. All relays used in this project contain user manuals on how to use the software and which parameters to program for certain fault conditions.

## VII. System Analysis/Data

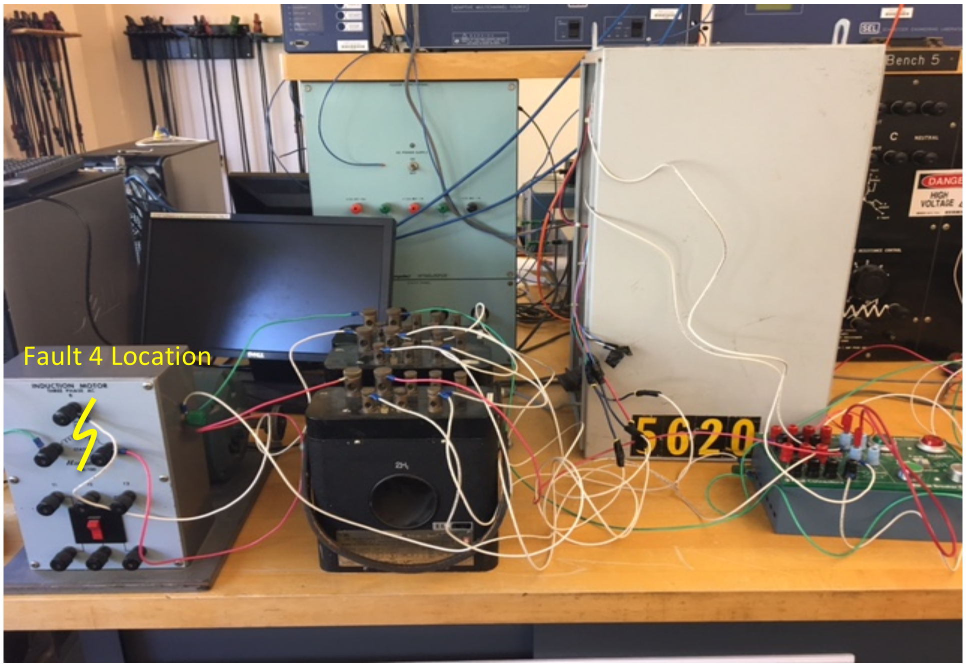


**Figure 22: System Fault 4 Location - Motor**

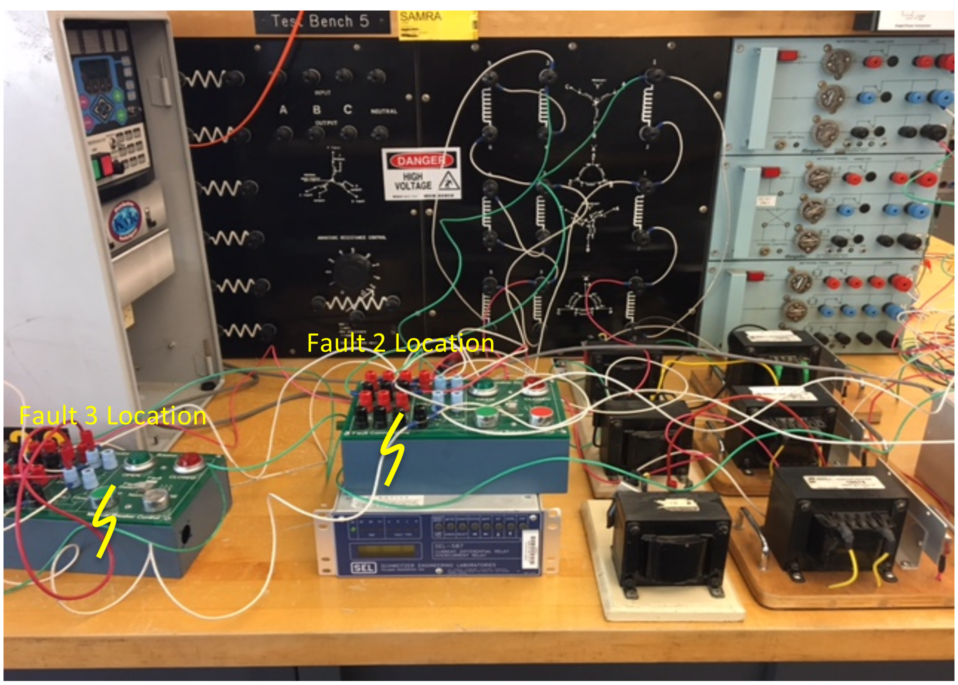


**Figure 23: System Fault 2 and 3 Locations – CB2 and CB3**

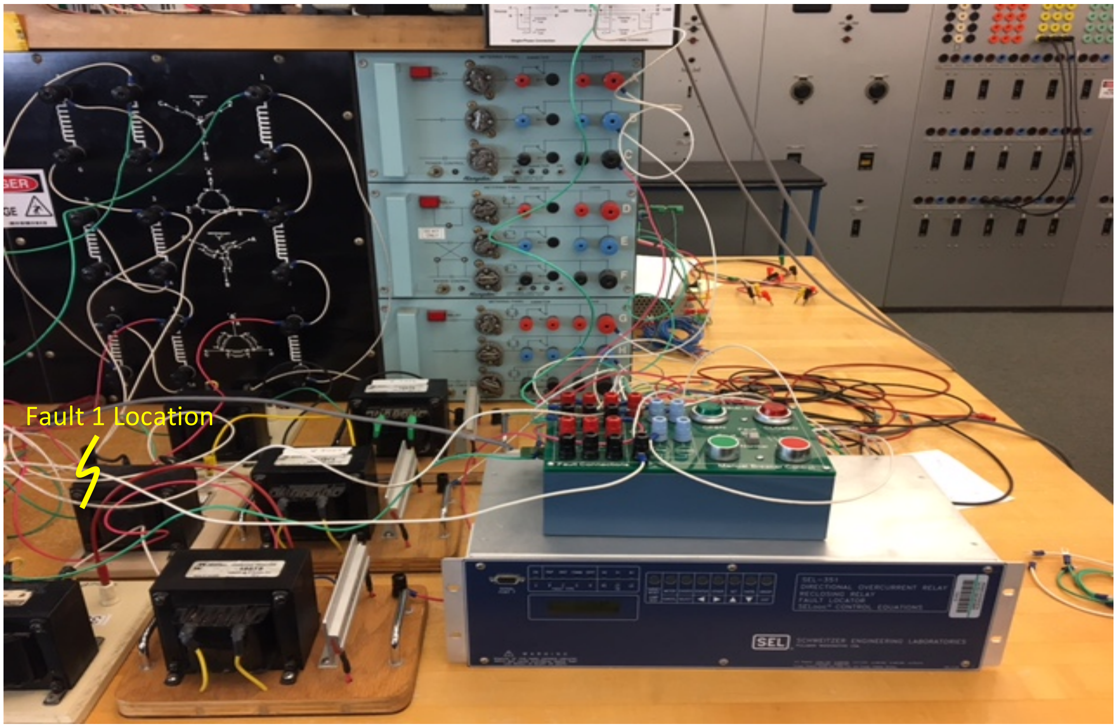


**Figure 24: System Fault 1 Location – End of Transmission Line**

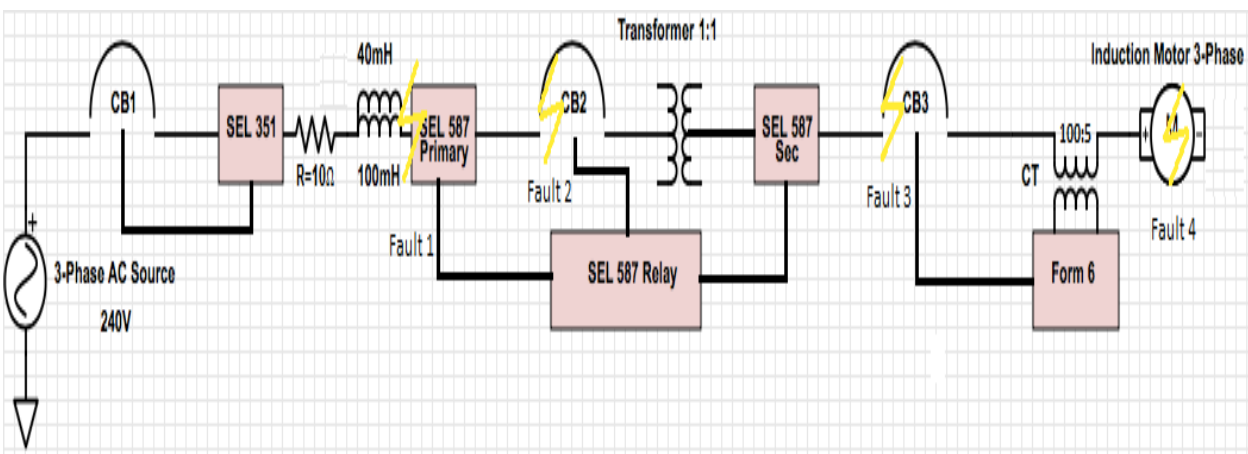


**Figure 25: System Single Line Circuit with Fault Locations**

Figures 22-24 above show the network connections for the project. The system contains four different fault locations, which are used to test the protection scheme. The first fault location is at the end of the transmission line to allow for impedance in the system. If the fault was created closer to the source, the impedance would be close to zero and the fault current would be very high. Faults 1 and 3 are both applied to visually see the SEL 351 relay trip before any other devices trip. The SEL 587 should not trip because the fault current is the same on the primary and secondary resulting in no current differential. The Form 6 Controller won't trip because the fault is upstream from the controller – meaning the Form 6 Controller does not see the fault. Fault 2 is within the transformer that allows the breaker to trip instantaneously from a current differential. Since the SEL-587 is instantaneous, the SEL-351 sees the fault, but the fault is already cleared by the SEL-587 relay. The last location is fault 4, which allows the Form 6 controller to trip and tests the coordination. When the motor is faulted, all devices see the overcurrent in the system, but the Form 6 Controller is the fastest to act upon the high current. Each fault location designated in Figure 25 above has a line-line and three-phase fault applied to it. Having two different fault conditions shows how the magnitude of the fault changes with the type of fault due to positive, negative, and zero sequence parameters. In a 3-phase fault, only the positive sequence is used to calculate the fault magnitude, while a line-line fault uses both positive and negative sequence. The data for each fault location is shown below.

## 1. Fault 1 – SEL 351 Trips for L-L and 3-Φ Faults

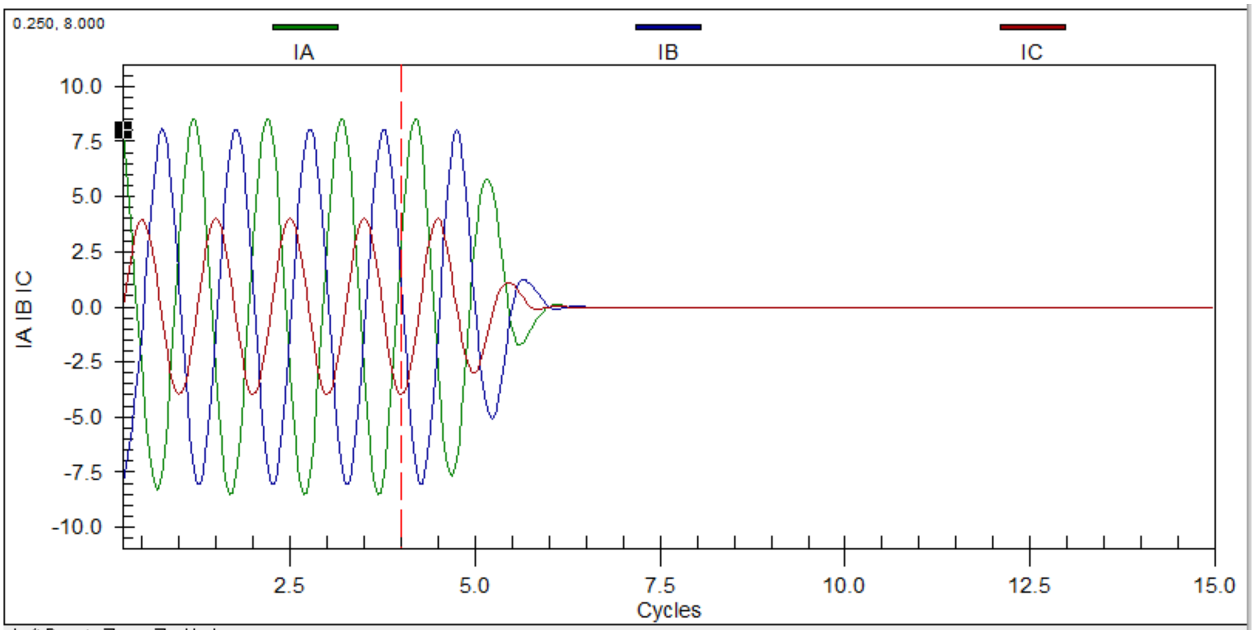


**Figure 26: L-L Fault Phase Currents**

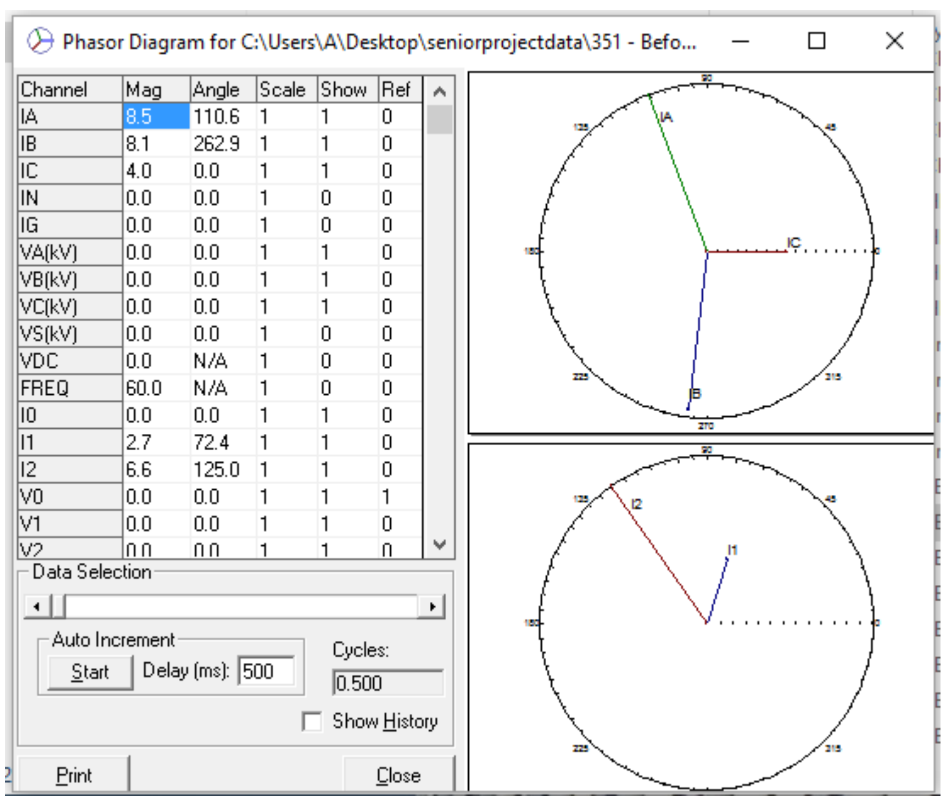


**Figure 27: L-L Phasor Diagram**

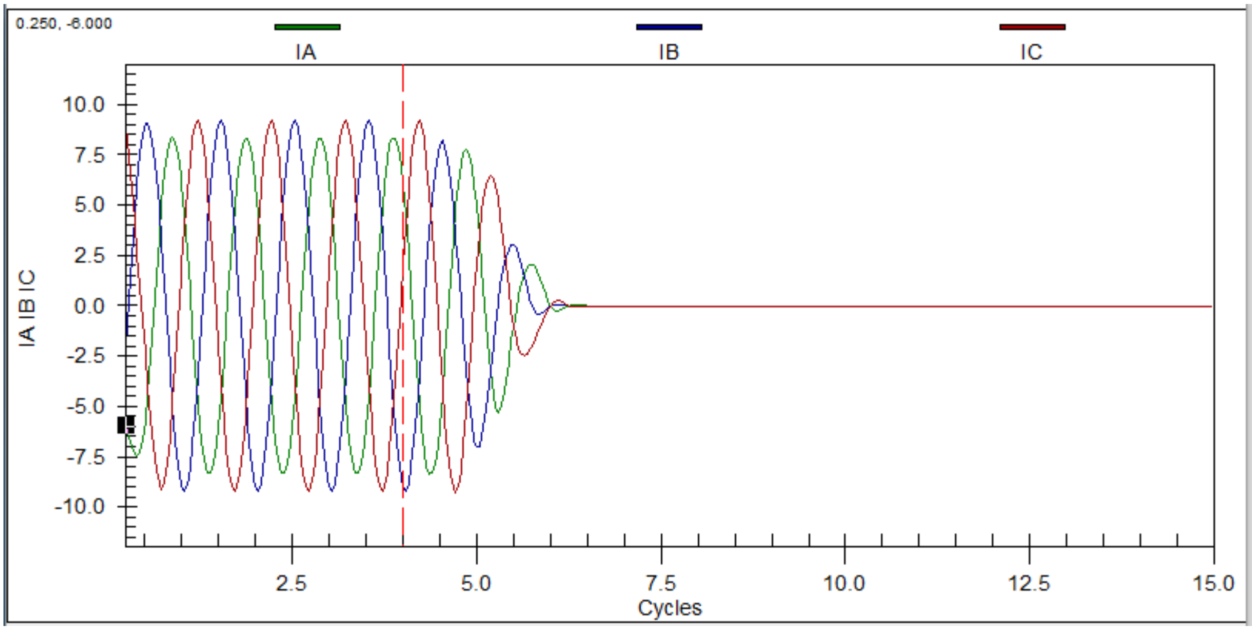


**Figure 28: 3-Φ Fault Phase Currents**

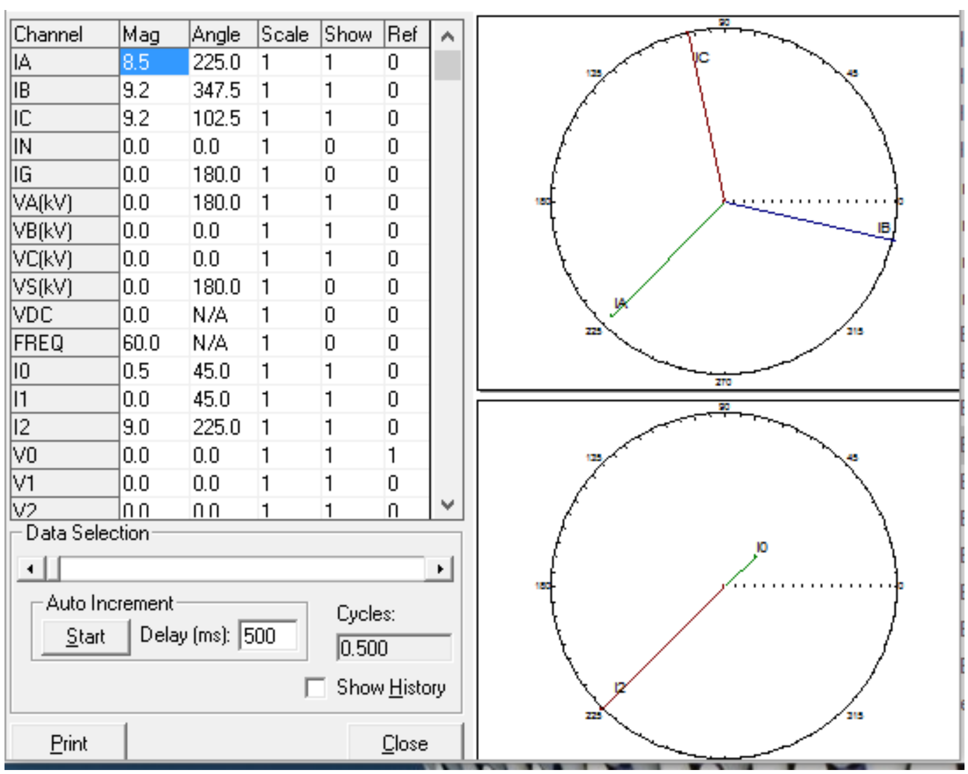


**Figure 29: 3-Φ Phasor Diagram**

The four figures above show the results of Fault 1 with line-line and three-phase fault applied. In both cases, the SEL 351 tells the breaker to open after 5 cycles of an overcurrent. Phases A and B are connected together to introduce the line-line fault and the data shows that both those phases have currents over 8A, while phase C only has 4A. For the three-phase fault, all phase are connected together and the result show equal amount of overcurrent on all three phases. The higher current amplitude in the three-phase exists because a three-phase fault only uses positive sequence when determining fault currents. The line-line fault uses both positive and negative, which results in a higher impedance.

## 2. Fault 2 – SEL 587 Trips for L-L and 3-Φ Faults

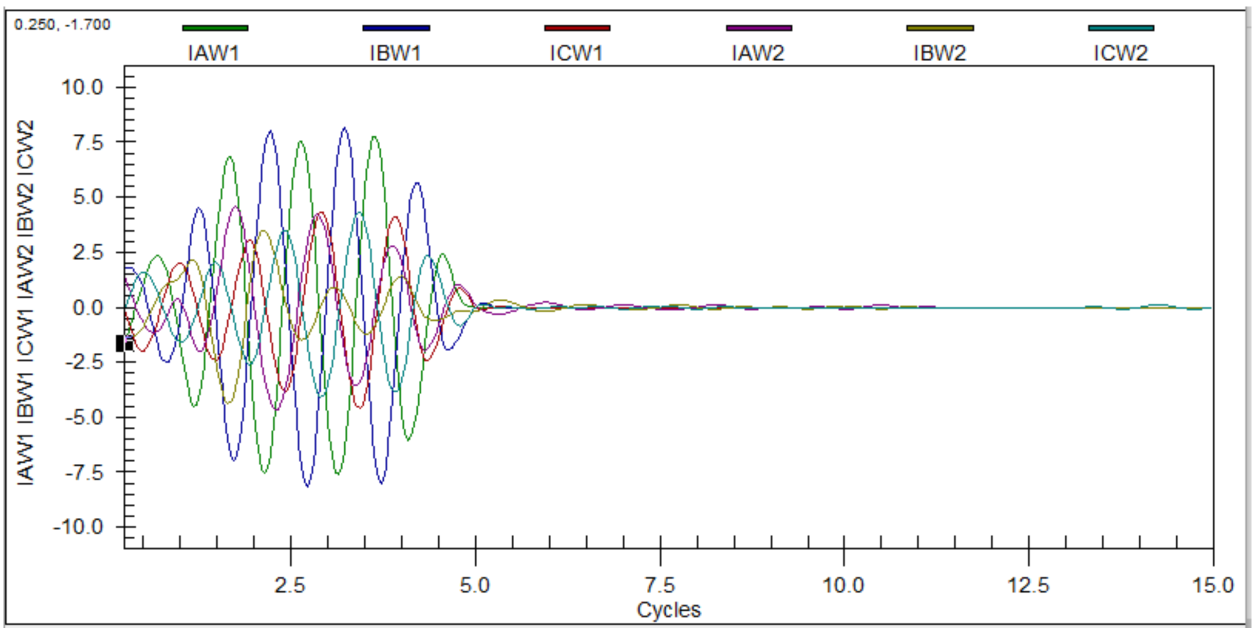


**Figure 30: L-L Fault Phase Currents**

Figure 30 above shows the fault currents on the primary and secondary side of the transformer when a line-line fault is introduced. It's hard to distinguish the magnitude of each phase, so Figure 32 below shows the current differential on phase B. Since the fault is line-line, only phase A and B alarm for the differential difference.

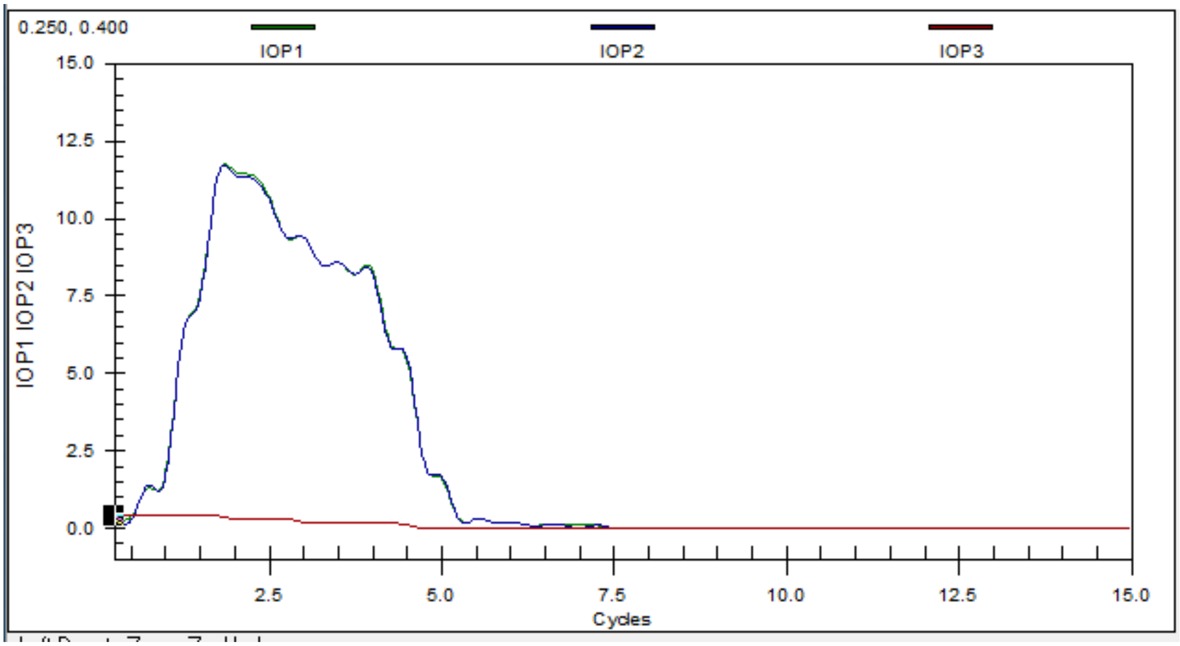


**Figure 31: L-L Fault IOP Plot**

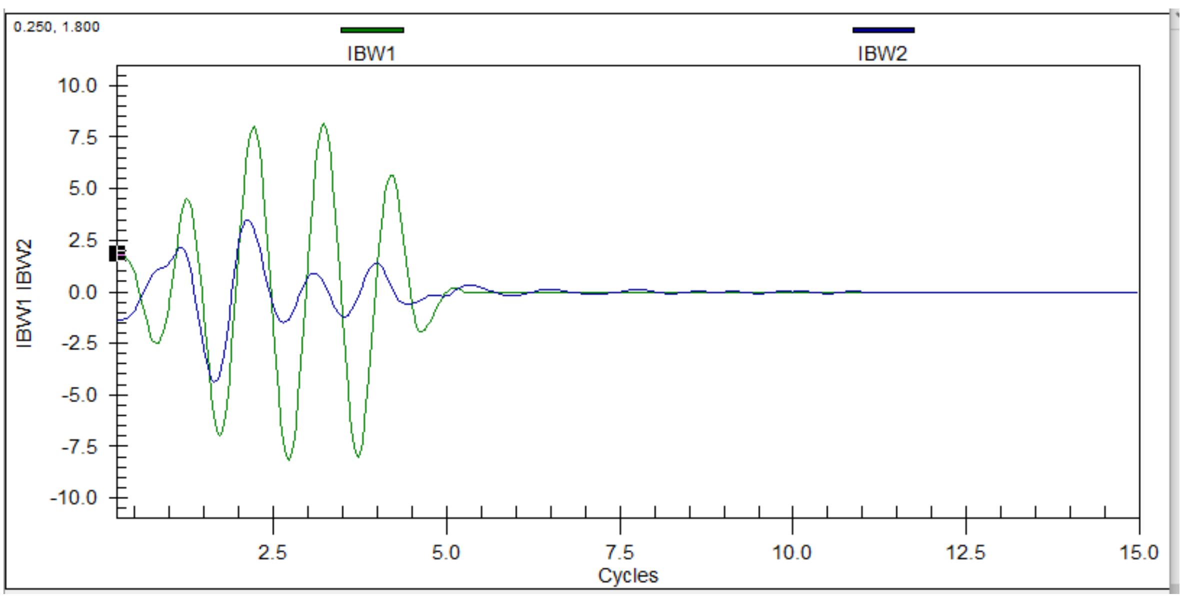


**Figure 32: L-L Fault Phase B Current Differential**

Figure 32 above shows primary and secondary currents for phase B. Curves are taken directly from Figure 30. Since the fault is within the transformer, the primary side sees excess current. The secondary current is fluctuating to zero because the motor is back feeding into the system. Within the second cycle, the secondary current has reached close to zero as expected.

The IOP curves in Figure 31 show that phases A and B have a current differential. Under normal operation, the primary and secondary currents are equal, which results in an IOP value close to zero. In the faulted case above, the current magnitude on the primary side is high and the current magnitude on the secondary is close to zero. The current differential between the two sides results in a high IOP value, since the currents running through the operating coil do not cancel. The maximum IOP value allowed before the breaker trips is set by the U87P parameter, which is set to 7.3A in the SEL-587 settings. As shown in Figure 31, the U87P value is exceeded for both phases.

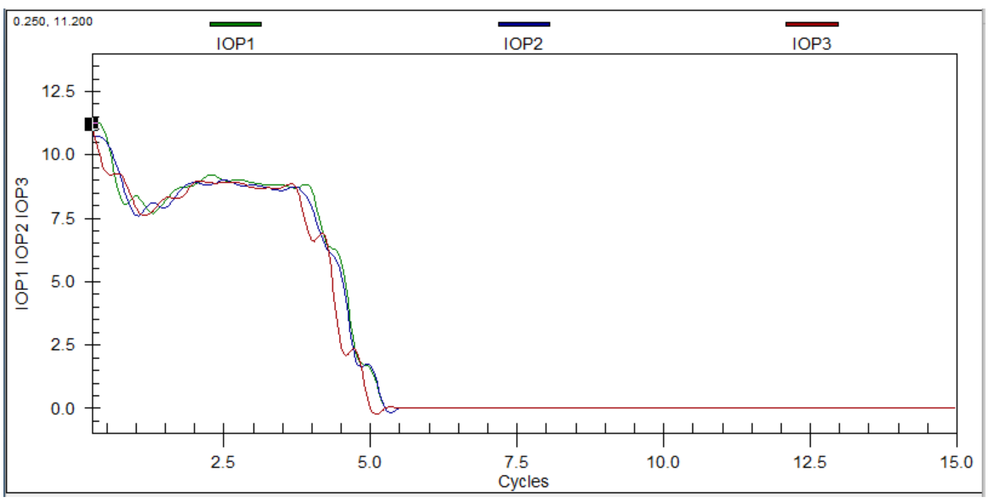


**Figure 33: 3-Φ IOP Plot**

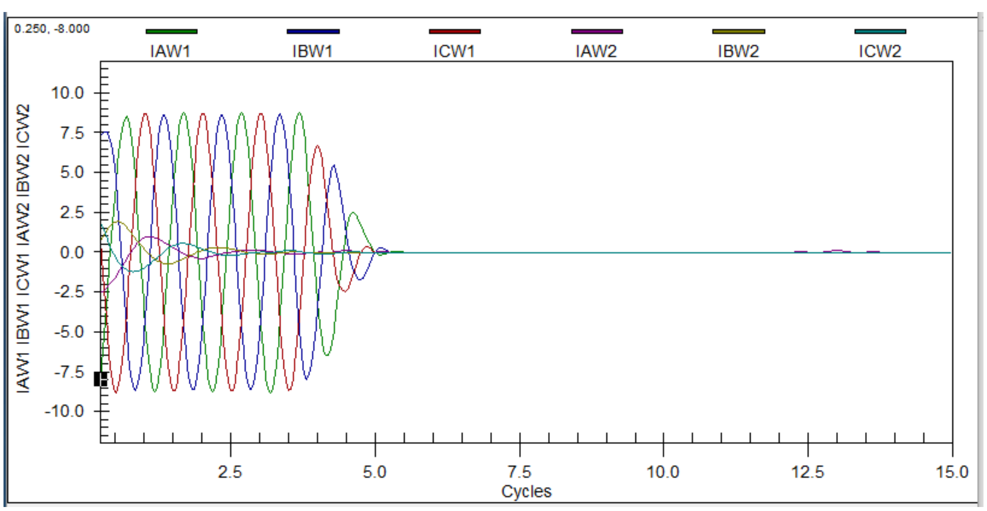


**Figure 34: 3-Φ Fault Phase Currents (Primary/Secondary)**

The same situation for the three-phase fault within the transformer follows. Each phase magnitude is much greater on the primary compared to the secondary, which tells the SEL-587 to trip the breaker instantaneously after five cycles. Compared to the previous IOP curve for the line-line fault, the IOP values in Figure 33 all exceed 7.3A, which initiates the trip.

## 3. Fault 3 – SEL 351 Trips for L-L and 3-Φ Faults

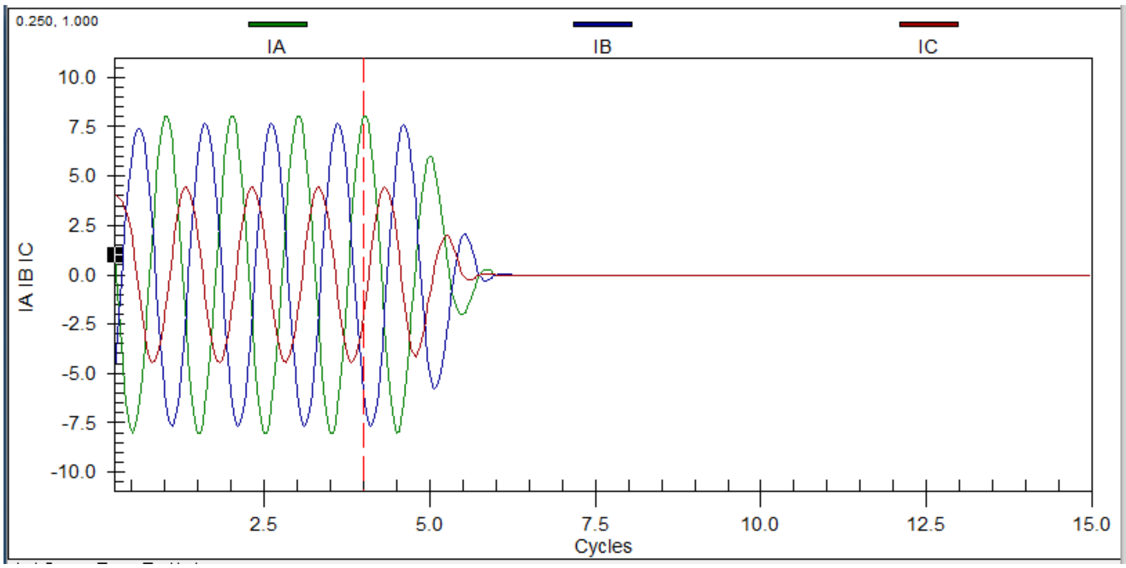


**Figure 35: L-L Fault Phase Currents**

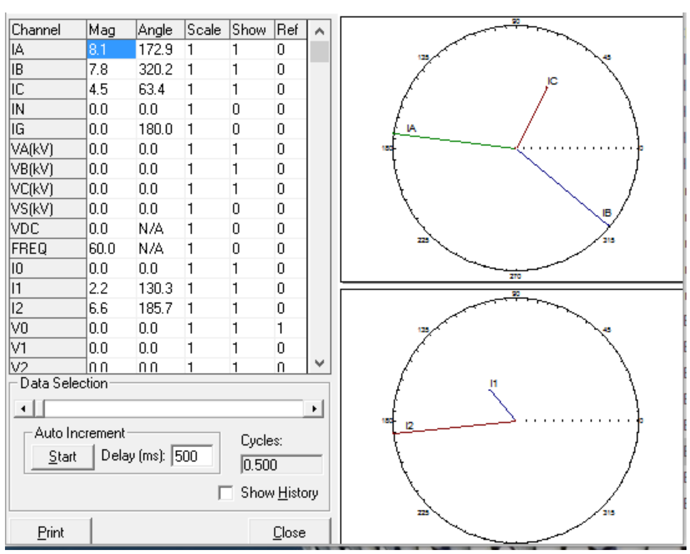


**Figure 36: L-L Phasor Diagram**

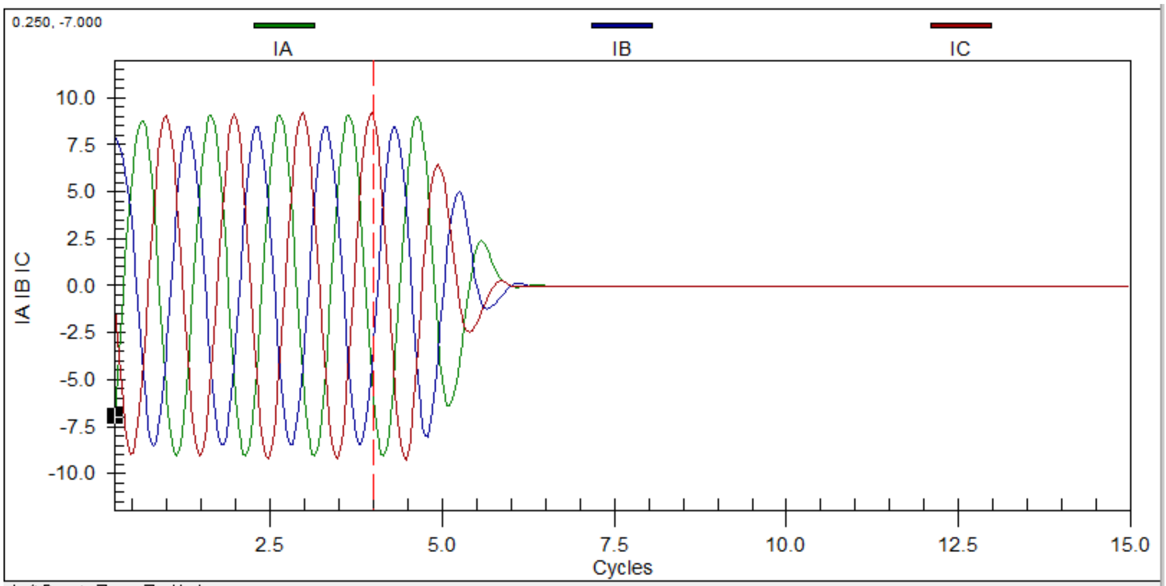


**Figure 37: 3-Φ Fault Phase Currents**

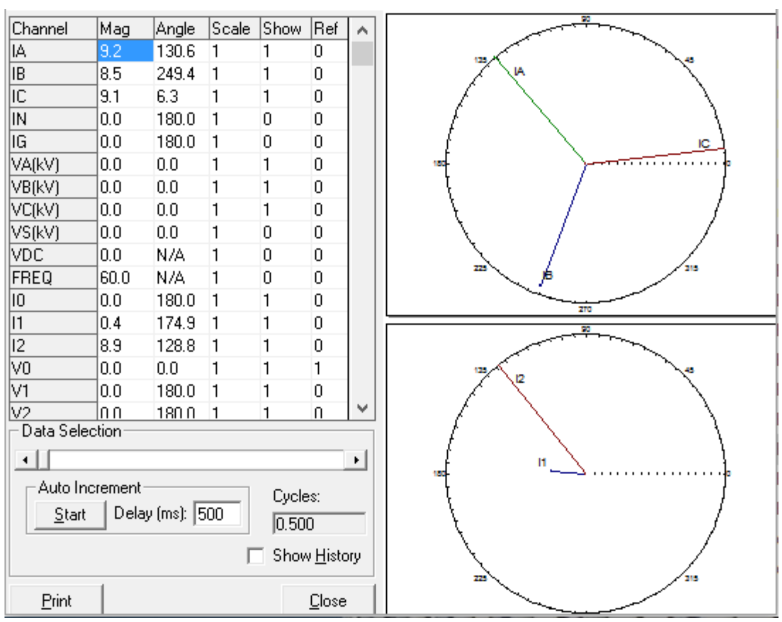


**Figure 38: 3-Φ Phasor Diagram**

Fault 3 uses the SEL-351 relay to trip on an overcurrent. Testing showed that the SEL-351 is the first to trip, since it's the first upstream device providing overcurrent protection. The SEL-587 does see the excess current, but doesn't trip for an overcurrent.

## 4. Fault 4 – Form 6 Controller Trips for L-L and 3-Φ Faults

Once the system receives power, the controller starts to pick-up current values. As shown in Figures 39 and 41, when a line-line or three-phase fault was applied, the breaker tripped after two cycles. Since the Form 6 Controller is at the end of the line, it acts as an instantaneous trip when a fault condition is present. The coordination between the Form 6 Controller and SEL-351 is important in this fault location because both relays see the fault. The coordination section above explains which curves were used for both relays to get the correct tripping. The first few trials, the SEL-351 tripped before the Form 6. Once the time-current curves were adjusted, the system worked as designed.

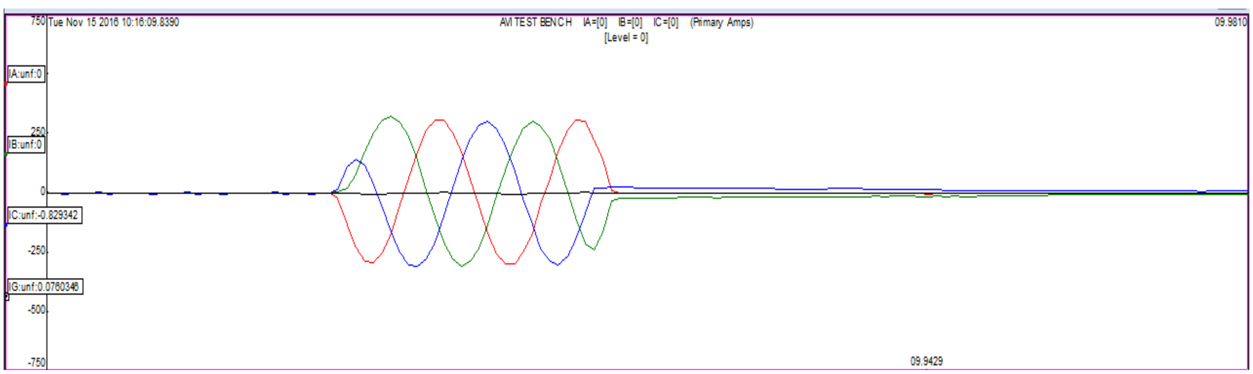


**Figure 39: 3-Φ Fault Phase Currents**

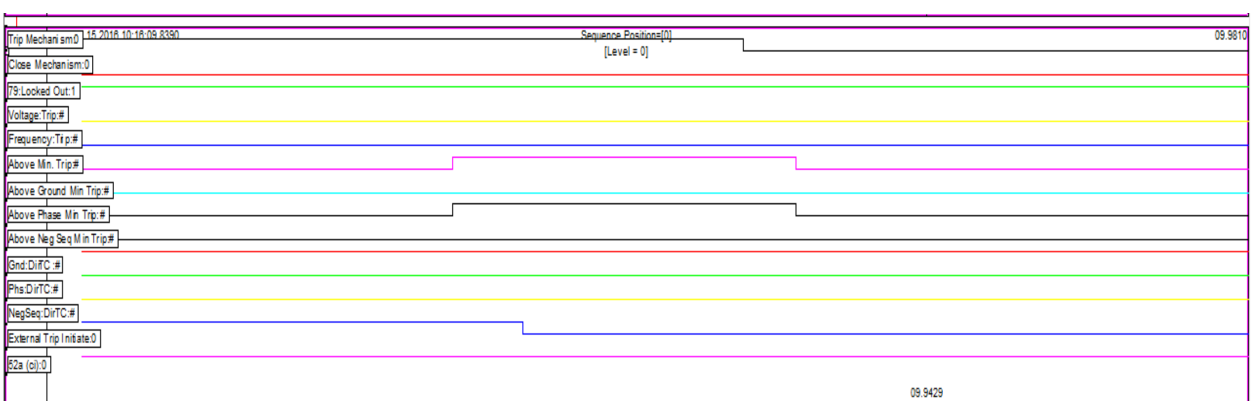


**Figure 40: 3-Φ Fault Logic Levels**

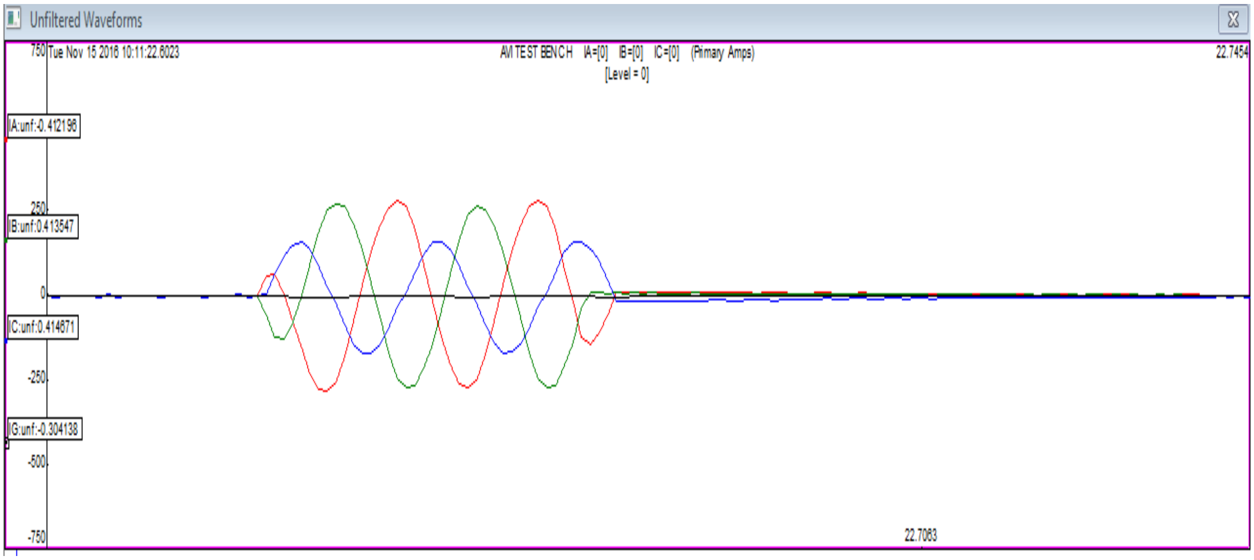


**Figure 41: L-L Fault Phase Currents**

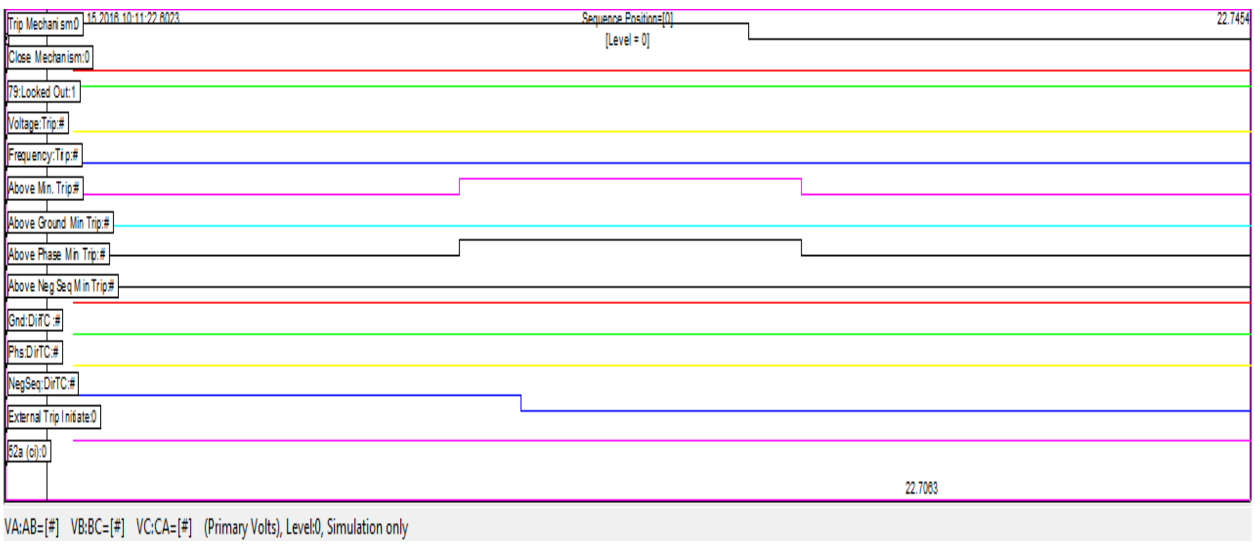


**Figure 42: L-L Fault Logic Levels**

## VIII. Conclusion

The overall project turned out to be a success. The initial design went through many adjustment phases to finally result a functional power system that could be tested in the lab. Each zone of the radial system was protected by a relay. The transmission line was protected by SEL-351 relay, the transformer was protected by SEL-587 relay, and the Form 6 Controller protected the motor. Each relay performed its assigned responsibility under line-line and three-phase fault conditions. A major component of the project was to come up with a protection scheme that protected the entire system and allowed for proper coordination. In all four different fault locations, the closest upstream device tripped the local breaker when a fault was present. One downfall of this project was not having the correct sized current transformer for the Form 6 Controller; this introduced some complications in measuring and tripping the breaker. Beside some other minor adjustments, the project was a great way to get hands on experience with industry standard equipment. The progression through electrical engineering courses allows for students to properly understand power system engineering concepts and apply them in industry. Using the knowledge obtained from these courses, a functioning small power distribution system design with a proper protection scheme was developed. In industry, both electromechanical and microprocessor relays are used for system protection, but the concept remains the same. After reading the user manuals, the settings were made based on the system design and programmed into the relay. The system construction and testing process provided good experience in power system protection. Another benefit of this project was familiarization with different relays used in industry.

# IX. References


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# Appendix A

## i. SEL 351 Settings

| Group | Setting | Value |
|---|---|---|
| 1 | RID | FEEDER 1 |
| 1 | TID | STATION A |
| 1 | CTR | 1 |
| 1 | CTRN | 1 |
| 1 | PTR | 1.00 |
| 1 | PTRS | 1.00 |
| 1 | Z1MAG | 14.70 |
| 1 | Z1ANG | 47.10 |
| 1 | Z0MAG | 14.70 |
| 1 | Z0ANG | 47.10 |
| 1 | Z0SMAG | 10.33 |
| 1 | Z0SANG | 45 |
| 1 | LL | 40.00 |
| 1 | E50P | N |
| 1 | E50N | N |
| 1 | E50G | N |
| 1 | E50Q | N |
| 1 | E51P | 1 |
| 1 | E51N | Y |
| 1 | E51G | N |
| 1 | E51Q | N |
| 1 | E32 | N |
| 1 | ELOAD | N |
| 1 | ESOTF | N |
| 1 | EVOLT | N |
| 1 | E25 | N |
| 1 | EFLOC | Y |
| 1 | ELOP | N |
| 1 | ECOMM | N |
| 1 | E81 | N |
| 1 | E79 | N |

| Group | Setting | Value |
|---|---|---|
| 1 | 67Q3D | 0.00 |
| 1 | 67Q4D | 0.00 |
| 1 | 51PP | 5 |
| 1 | 51PC | U5 |
| 1 | 51PTD | 1 |
| 1 | 51PRS | Y |
| 1 | 51AP | OFF |
| 1 | 51AC | U3 |
| 1 | 51ATD | 3.00 |
| 1 | 51ARS | N |
| 1 | 51BP | OFF |
| 1 | 51BC | U3 |
| 1 | 51BTD | 3.00 |
| 1 | 51BRS | N |
| 1 | 51CP | OFF |
| 1 | 51CC | U3 |
| 1 | 51CTD | 3.00 |
| 1 | 51CRS | N |
| 1 | 51NP | 3.000 |
| 1 | 51NC | U3 |
| 1 | 51NTD | 5.00 |
| 1 | 51NRS | N |
| 1 | 51GP | OFF |
| 1 | 51GC | U3 |
| 1 | 51GTD | 1.50 |
| 1 | 51GRS | N |
| 1 | 51QP | OFF |
| 1 | 51QC | U3 |
| 1 | 51QTD | 3.00 |
| 1 | 51QRS | N |
| 1 | ZLF | 6.50 |

| Group | Setting | Value |
|---|---|---|
| G | TGR | 180.00 |
| G | NFREQ | 60 |
| G | PHROT | ACB |
| G | DATE_F | MDY |
| G | FP_TO | 15 |
| G | LER | 15 |
| G | PRE | 4 |
| G | DCLOP | OFF |
| G | DCHIP | OFF |
| G | IN1D | 0.50 |
| G | IN2D | 0.50 |

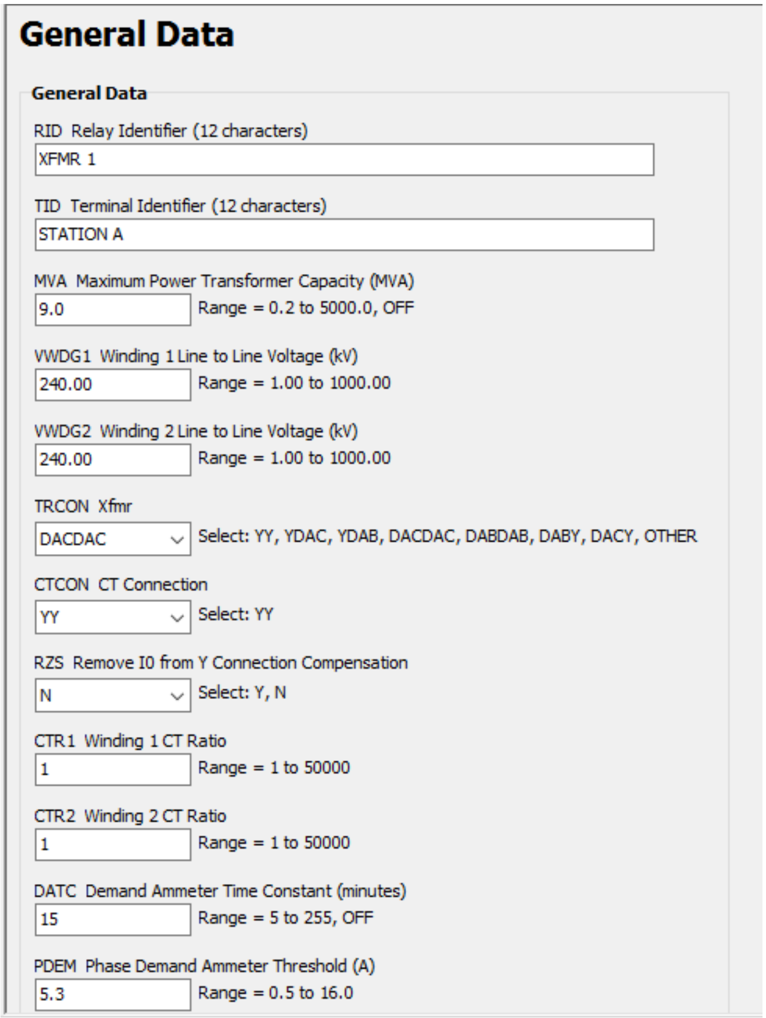
| Group | Setting | Value |
|---|---|---|
| L1 | TR | 51PT |
| L1 | TRCOMM | 0 |
| L1 | TRSOTF | 0 |
| L1 | DTT | 0 |
| L1 | ULTR | !(51P + 51G) |
| L1 | PT1 | 0 |
| L1 | LOG1 | 0 |
| L1 | PT2 | 0 |
| L1 | LOG2 | 0 |
| L1 | BT | 0 |
| L1 | 52A | IN101 |
| L1 | CL | CC + LB4 |
| L1 | ULCL | TRIP |
| L1 | 79RI | TRIP |
| L1 | 79RIS | 52A + 79CY |
| L1 | 79DTL | OC + !IN102 + LB3 |
| L1 | 79DLS | 79LO |
| L1 | 79SKP | 0 |
| L1 | 79STL | TRIP |
| L1 | 79BRS | 0 |
| L1 | 79SEQ | 0 |
| L1 | 79CLS | 1 |
| L1 | SET1 | 0 |
| L1 | RST1 | 0 |
| L1 | SET2 | 0 |
| L1 | RST2 | 0 |
| L1 | SET3 | 0 |
| L1 | RST3 | 0 |
| L1 | SET4 | 0 |
| L1 | RST4 | 0 |
| L1 | SET5 | 0 |

| Group | Setting | Value |
|---|---|---|
| L1 | SV15 | 0 |
| L1 | SV16 | 0 |
| L1 | OUT1 | 0 |
| L1 | OUT2 | 0 |
| L1 | OUT3 | 0 |
| L1 | OUT4 | 0 |
| L1 | OUT5 | 0 |
| L1 | OUT6 | 0 |
| L1 | OUT7 | 0 |
| L1 | OUT8 | 0 |
| L1 | OUT9 | 0 |
| L1 | OUT10 | 0 |
| L1 | OUT11 | 0 |
| L1 | OUT101 | !TRIP |
| L1 | OUT102 | 0 |

| | | |
|---|---|---|
| L1 | SS6 | 0 |
| L1 | ER | /51P + /51G + /OUT101 |
| L1 | FAULT | 51P + 51G |
| L1 | BSYNCH | 52A |
| L1 | CLMON | 0 |
| L1 | BKMON | TRIP |
| L1 | E32IV | 1 |
| L1 | TMB1A | 0 |
| L1 | TMB2A | 0 |
| L1 | TMB3A | 0 |
| L1 | TMB4A | 0 |
| L1 | TMB5A | 0 |
| L1 | TMB6A | 0 |
| L1 | TMB7A | 0 |
| L1 | TMB8A | 0 |
| L1 | TMB1B | 0 |
| L1 | TMB2B | 0 |
| L1 | TMB3B | 0 |
| L1 | TMB4B | 0 |
| L1 | TMB5B | 0 |
| L1 | TMB6B | 0 |
| L1 | TMB7B | 0 |
| L1 | TMB8B | 0 |

| Group | Setting | Value |
|---|---|---|
| P3 | PROTO | SEL |
| P3 | PREFIX | @ |
| P3 | ADDR | 1 |
| P3 | SETTLE | 0 |
| P3 | SPEED | 19200 |
| P3 | RTSCTS | N |
| P3 | RBADPU | 60 |
| P3 | CBADPU | 1000 |
| P3 | RXID | 1 |
| P3 | TXID | 2 |

## ii. SEL 587 Settings



### General Data

**General Data**

RID Relay Identifier (12 characters)
XFMR 1

TID Terminal Identifier (12 characters)
STATION A

MVA Maximum Power Transformer Capacity (MVA)
9.0 Range = 0.2 to 5000.0, OFF

VWDG1 Winding 1 Line to Line Voltage (kV)
240.00 Range = 1.00 to 1000.00

VWDG2 Winding 2 Line to Line Voltage (kV)
240.00 Range = 1.00 to 1000.00

TRCON Xfmr
DACDAC Select: YY, YDAC, YDAB, DACDAC, DABDAB, DABY, DACY, OTHER

CTCON CT Connection
YY Select: YY

RZS Remove I0 from Y Connection Compensation
N Select: Y, N

CTR1 Winding 1 CT Ratio
1 Range = 1 to 50000

CTR2 Winding 2 CT Ratio
1 Range = 1 to 50000

DATC Demand Ammeter Time Constant (minutes)
15 Range = 5 to 255, OFF

PDEM Phase Demand Ammeter Threshold (A)
5.3 Range = 0.5 to 16.0

# Differential Elements

**Differential Elements**

O87P Operating Current PU (TAP)
0.4 Range = 0.1 to 1.0

SLP1 Restraint Slope 1 (%)
40 Range = 5 to 100

SLP2 Restraint Slope 2 (%)
OFF Range = 25 to 200, OFF

IRS1 Restraint Current Slope 1 Limit (TAP)
3.0 Range = 1.0 to 16.0

U87P Inst Unrestrained Current PU (TAP)
7.3 Range = 1.0 to 16.0

PCT2 2nd Harmonic Blocking Percentage (%)
15 Range = 5 to 100, OFF

PCT4 4th Harmonic Blocking Percentage (%)
15 Range = 5 to 100, OFF

PCT5 5th Harmonic Blocking Percentage (%)
35 Range = 5 to 100, OFF

TH5 5th Harmonic Threshold (TAP)
0.4 Range = 0.1 to 3.2

TH5D 5th Harmonic Alarm TDPU (cyc)
30.000 Range = 0.000 to 8000.000

DCRB DC Ratio Blocking
Y Select: Y, N

HRSTR Harmonic Restraint
Y Select: Y, N

# PWR System Data

**PWR System Data**

NFREQ Nominal Frequency (Hz)

60 — Select: 50, 60

PHROT Phase Rotation

ACB — Select: ABC, ACB

# Logic

**SELogic Settings**

X (SELogic Equation)

87R+87U

Y (SELogic Equation)

NA

MTU1 (SELogic Equation)

87U+87R

MTU2 (SELogic Equation)

51P1P

MTU3 (SELogic Equation)

51P1P

MER (SELogic Equation)

87R+87U

OUT1 (SELogic Equation)

!TRP1

OUT2 (SELogic Equation)

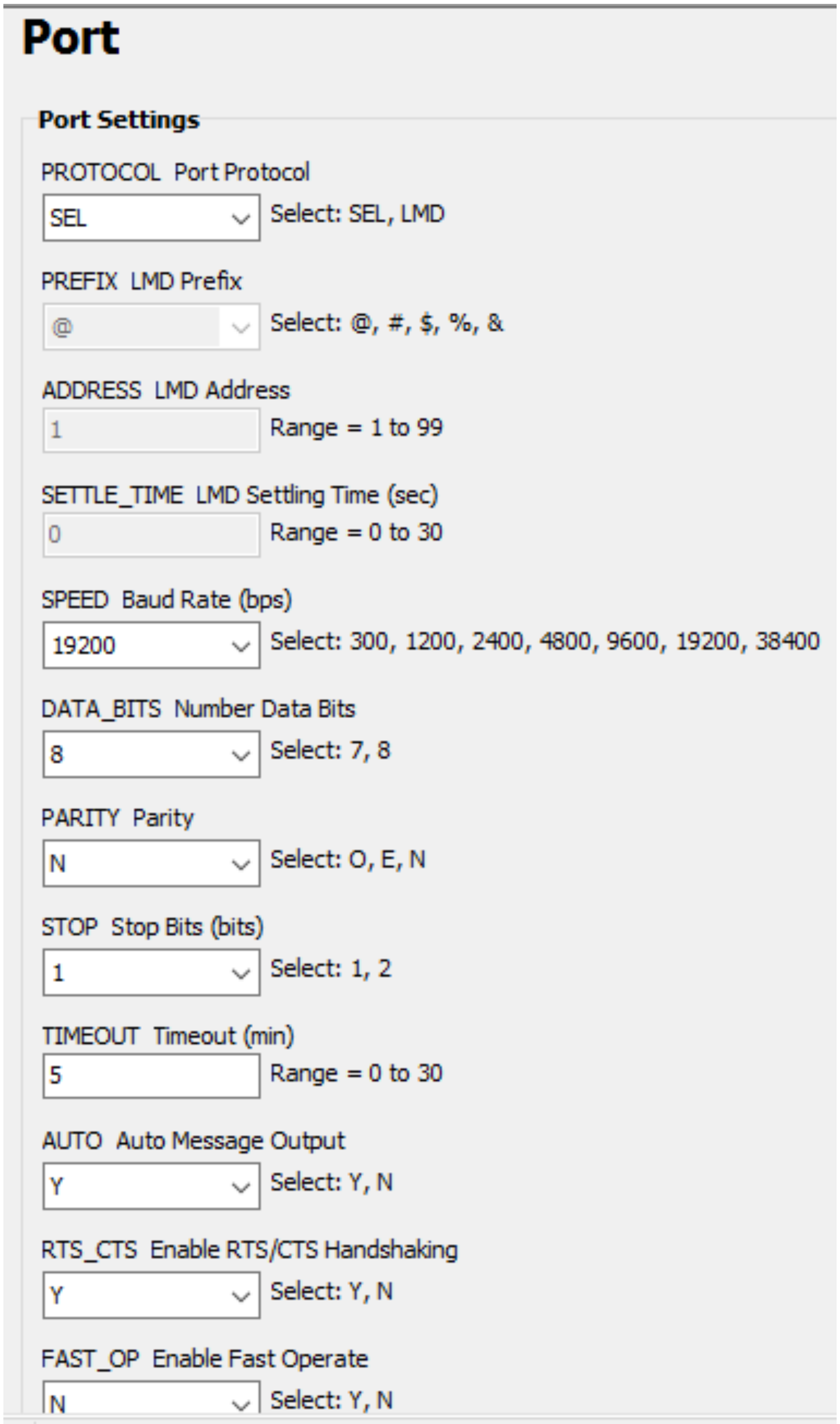
TRP2

OUT3 (SELogic Equation)

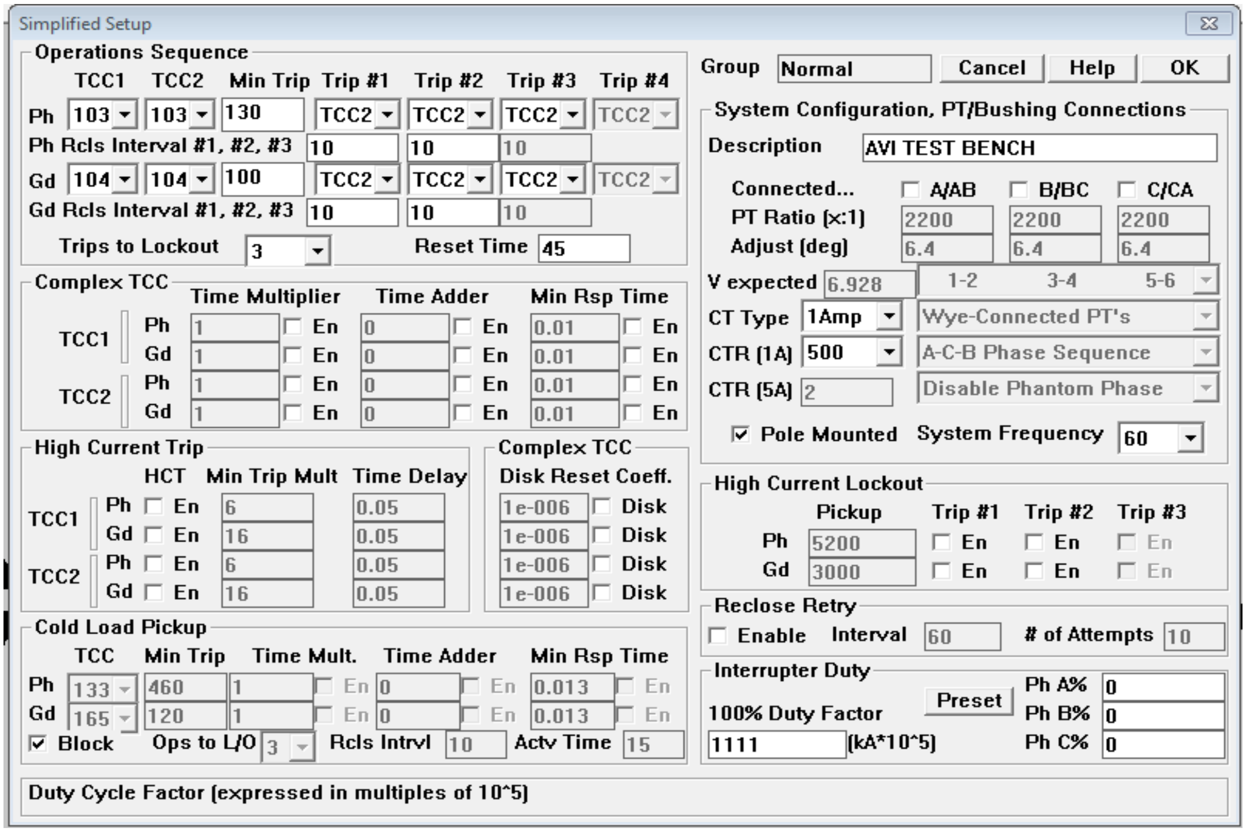
TRP3

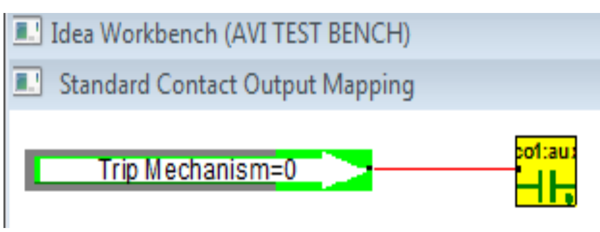
OUT4 (SELogic Equation)

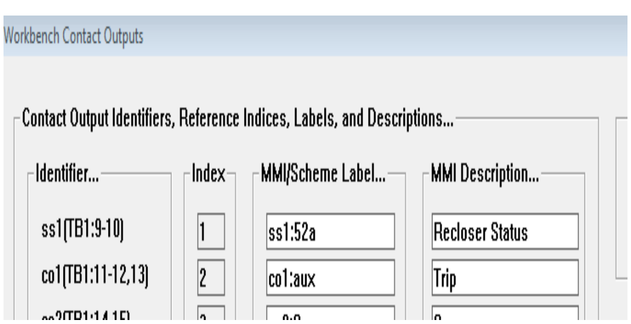
87R+87U+50P1T+51P1T+50Q1T+51Q1T+50P2T+51P2T+51N2T

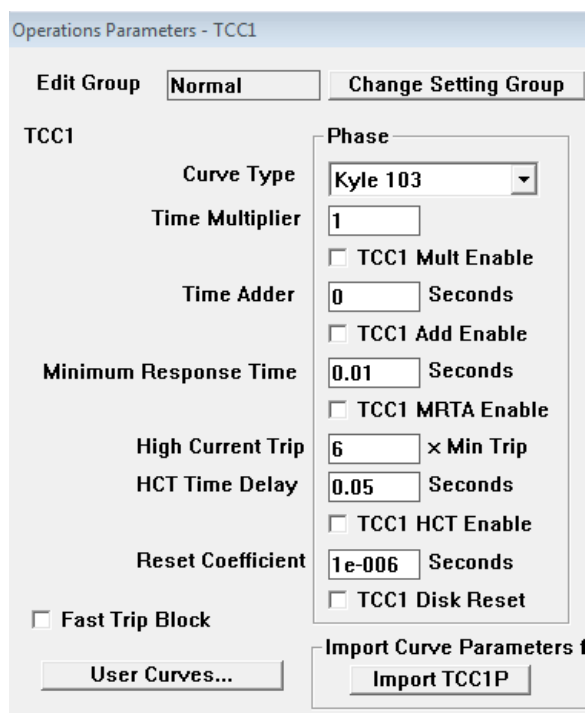

Port
Port Settings
PROTOCOL Port Protocol
SEL
Select: SEL, LMD
PREFIX LMD Prefix
@
Select: @, #, $, %, &
ADDRESS LMD Address
1
Range = 1 to 99
SETTLE_TIME LMD Settling Time (sec)
0
Range = 0 to 30
SPEED Baud Rate (bps)
19200
Select: 300, 1200, 2400, 4800, 9600, 19200, 38400
DATA_BITS Number Data Bits
8
Select: 7, 8
PARITY Parity
N
Select: O, E, N
STOP Stop Bits (bits)
1
Select: 1, 2
TIMEOUT Timeout (min)
5
Range = 0 to 30
AUTO Auto Message Output
Y
Select: Y, N
RTS_CTS Enable RTS/CTS Handshaking
Y
Select: Y, N
FAST_OP Enable Fast Operate
N
Select: Y, N

## iii. Copper Form 6 Controller Settings




NOTE: Ground tripping was not used due to delta system.