DIFFERENTIAL TRANSFORMER PROTECTION USING THE SEL 387 AND SEL 587 MICROPROCESSOR RELAYS

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Acknowledgements
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Abstract

The objective of this Senior Project is to use the SEL 387 current differential and overcurrent microprocessor relays to protect three-single-phase 1 KVA 120:208 transformers configured in Δ-Δ, Y-Y, Y-Δ, and Δ-Y connections. In the second phase of this project, is to create a functioning lab that uses the SEL 587 relay to teach basic differential transformer protection for the upcoming EE-444 students.

The protection schemes developed in both of the senior project phases require the use of differential and overcurrent protection elements by monitoring the changes of the input and output current through the transformer. When these currents fail to match, in the case of a fault, or reach a specified current set point, the relay must trip. Experimentally, these differential protection schemes will be tested by flipping the polarity of the currents going into the relay to simulate an internal fault in the transformer. Afterwards, the event report generated by the relay will be analyzed to verify the results. Because of safety limitations regarding circuit breakers, the overcurrent element will not be tested in this senior project.

The EE-444 lab will follow the same design and test procedure for the first phase of the senior project. However, the lab will use the SEL 587 in place of the SEL 387, the same 3 KVA transformers on the lab bench, and will only test the differential protection for the Y-Y transformer configuration.
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I. **Introduction and Background**

Power transformers are a major power system component in a utility in order to maintain economic power transmission with high efficiency. Since electric power is proportional to the product of voltage and current \((V \times I)\), low current levels can be maintained for given power levels via high voltages when using transformers [3]. This concept allows power transformers to bring voltages to optimum levels for generation, transmission, and distribution.

Because transformers are found throughout, the power system transformer protection is essential to having a reliable power system. If there were no means of electrical protection, through faults will travel further upstream leading to catastrophic failure of main transformers and eventually other parts of the power system. When electrical protection is performed with relays, the faulted equipment is separated, leaving the rest of the power system intact and operational. This practical solution enables electrical engineers to have a reliable power system.

The main objective of transformer protection is to provide the ability to detect internal transformer faults with a high degree of sensitivity [4]. By having sensitive detection and de-energization of internal faults limits, the internal damage caused to the transformer, which results in low downtime, and lower repair costs.

It is common practice to use differential and overcurrent protection to protect transformers [2]. However, various system conditions indirectly affect the health of transformers. For example, transformer loadings that exceed transformer nameplate ratings or overcurrent caused by external faults can cause the temperature of the windings to rise beyond the rated limits [1]. In addition, over excitation of a transformer causes eddy currents in the core, which can result in overheating. In addition
to faults, the design of transformer protection needs to consider these issues related to overloads, overcurrent, and over excitation.

### 2.1 Electromechanical Relay

In past generations, installing electromechanical relays as shown in Figure 1 were the only means of implementing this type of protection. The major disadvantage of the electromechanical relay is that it is a “mechanical device.” For one, the electromechanical relays contain moving parts so their switching speed (response time) are slow due to the magnetic field physically moving the metal contacts as shown in Figure 2. These electromechanical relays become less reliable if the relay trips often enough over time. Due to the constant arcing and erosion caused by constant tripping, the metal contacts will begin to corrode and become prone to failure [10].

![Electromechanical Relay](image1.png)

*Figure 1 Westinghouse Differential Electromechanical Relay [8]*

![Electromechanical Switch](image2.png)

*Figure 2 Electromechanical Switch [10]*
2.2 Microprocessor Relay

The modern equivalent of electromechanical relays is the microprocessor based relays as shown in Figure 3. By installing this microprocessor relay in this transformer, overcomes the limitations of mechanical switches and contacts by replacing them with transistors (Logic Gates). The main advantage of the microprocessor relay over the electromechanical relay is the ability to review output event files. When a fault occurs, the relay saves an event allowing engineers to analyze fault data.

Figure 3 SEL 387 Overcurrent Differential Relay [6]

Figure 4 Functional Diagram of the SEL 387 [6]
The functional diagram as shown in Figure 4 displays the different types of relays in the SEL 387.

The user has to input transformer parameters into the SEL 387 via the AcSELerator QuickSet program.

Once inputted the user has to specify which relay elements are appropriate for the transformer and select the specified settings to send to the relay.

### Table 1 Advantages and Disadvantages of the SEL 387 Current Differential Relay

<table>
<thead>
<tr>
<th>Advantages of the SEL 387</th>
<th>Disadvantages of the SEL 387</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased electrical reliability due to the lack of moving parts [10]</td>
<td>If the whole unit is corrupted, all relays are lost and the user must take the asset out of service</td>
</tr>
<tr>
<td>Smaller footprint because all required relays are installed into one unit</td>
<td>Subject to cyber security</td>
</tr>
<tr>
<td>Self-diagnostics of the unit allows the users to know when a relay is not operational [6]</td>
<td></td>
</tr>
<tr>
<td>AcSELerator Analytic Assistant provides phasor diagrams that help support commissioning and troubleshooting [6]</td>
<td></td>
</tr>
<tr>
<td>Ability to monitor instantaneous measurements of phase and demand current [6]</td>
<td></td>
</tr>
<tr>
<td>Notify users when to schedule breaker maintenance [6]</td>
<td></td>
</tr>
<tr>
<td>When a fault occurs, the microprocessor relay is able to record event history, which can be used for future troubleshooting [6]</td>
<td></td>
</tr>
<tr>
<td>Relay and Logic Setting software reduces engineering costs for relay settings and logic programming [6]</td>
<td></td>
</tr>
</tbody>
</table>
Table 2 Features and Disadvantages of the Electromechanical Relay

<table>
<thead>
<tr>
<th>Features of Electromechanical Relays</th>
<th>Disadvantages of the Electromechanical Relays</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uses heavy duty parts made from iron and steel, making the relay more robust [10]</td>
<td>Decreased electrical reliability due to moving parts [10]</td>
</tr>
<tr>
<td>Longer life span when compared to microprocessor relays [10]</td>
<td>Contacts eventually wear out and corrode over a period of continually use [10]</td>
</tr>
<tr>
<td>Requires more relays in order to implement a full protection scheme</td>
<td>Unable to do self-diagnostics of the unit allows the users to know when a relay is not operational</td>
</tr>
<tr>
<td>Impervious to cyber attacks</td>
<td>Not able to produce phasor diagrams or oscillography results to assist engineers during troubleshooting</td>
</tr>
<tr>
<td></td>
<td>Does not possess the ability to monitor instantaneous measurements of phase and demand current</td>
</tr>
<tr>
<td></td>
<td>Does not notify users when to schedule breaker maintenance</td>
</tr>
<tr>
<td></td>
<td>Not able to record event history, which can be used for future troubleshooting</td>
</tr>
</tbody>
</table>

Table 1 and Table 2 outline the advantages and disadvantages of the electromechanical relay and microprocessor relays. According to Table 1, it is clear that the introduction of the SEL 387 current differential relay outweigh the drawbacks that it possesses. By having these additional features, engineers are able to install, maintain, and manage the transformer. Even though electromechanical relays have been around over a hundred years, the need for more functionality as described in Table 1 is necessary to improve the electrical reliability of the power-engineering field.
II. Block Diagram, Requirements, and Specifications

3.1 Block Diagram 1

![Figure 5 Implementation of the Electrical Protection in Block Diagram Form](image1)

The block diagram of the protection design is shown in Figure 5. To the input of the SEL 387 Differential and Overcurrent Relay, is a computer with the AcSELerator QuickSet Program that communicates via a serial port. From there the computer will program the SEL 387 to trip if the transformer experiences a fault. This system uses 120:208 single-phase transformers connected in Δ-Δ, Y-Y, Y-Δ, and Δ-Y topologies in the design.

3.2 Block Diagram 2

![Figure 6 Implementation of the Electrical Protection for the Lab in Block Diagram Form](image2)

The block diagram of the protection design for the lab is shown in Figure 6. The setup is essentially the same as Figure 5; however, the relay, transformers, and transformer topologies are different. The SEL 587 relay is used to sense and react to abnormalities within the zone of protection. Instead of using the 120:208 single-phase transformers, 240:120 single-phase transformers are used in this design and only the Y-Y transformer configuration will be implemented in the protection system.
Table 3 Summary SEL 387/587 Relay Functional Description

<table>
<thead>
<tr>
<th>Module</th>
<th>SEL 387/587 Relay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td>Relay currents stepped down from the instrumentation current transformers. These</td>
</tr>
<tr>
<td></td>
<td>currents should not exceed 10 Amps and should not be below 0.5 Amps.</td>
</tr>
<tr>
<td>Outputs</td>
<td>SEL 387/587 Relay HMI will display A, B, and C phase of where the simulated fault</td>
</tr>
<tr>
<td></td>
<td>occurred. In addition, the relay will output a specified event report for analysis.</td>
</tr>
<tr>
<td>Functionality</td>
<td>When there is a simulated (flipping of polarity), internal fault within the</td>
</tr>
<tr>
<td></td>
<td>transformer, the SEL 387/587 relay will trip and an event report will be</td>
</tr>
<tr>
<td></td>
<td>generated for analysis.</td>
</tr>
</tbody>
</table>

Table 3 describes the inputs/outputs of the SEL 387/587 Relay as well as the functionality of the device. In the functionality module, describes how the relay be tested and commissioned. Essentially, the relay will be tested for an internal fault and the electrical protection system will output an event report for analysis.

3.3 Requirements and Specifications

Table 4 Material Requirements and Specifications

<table>
<thead>
<tr>
<th>Material</th>
<th>Specifications</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1 Transformer</td>
<td>3-Single Phase Transformers 120:208</td>
<td>Transformers need to be different from the ones found in the EE 444 lab to</td>
</tr>
<tr>
<td></td>
<td></td>
<td>have diverse relay settings from phase 2 of the senior project.</td>
</tr>
<tr>
<td>Phase 2 Transformer</td>
<td>3-Single Phase Transformers 240:120</td>
<td>These transformer are for EE 444 lab</td>
</tr>
<tr>
<td>Current Transformer</td>
<td>Multi-tap CT Ratios Preferably 10:5</td>
<td>Multi-tap CT Ratios are necessary to provide a suitable value of current for</td>
</tr>
<tr>
<td></td>
<td></td>
<td>the instrument relay</td>
</tr>
<tr>
<td>SEL 387 Relay</td>
<td>Differential and Overcurrent Relay</td>
<td>EE Senior Project</td>
</tr>
<tr>
<td>SEL 587 Relay</td>
<td>Differential and Overcurrent Relay</td>
<td>EE 444 Lab</td>
</tr>
<tr>
<td>Leads and Connections</td>
<td>14 AWG</td>
<td>This wire gauge current limit is suitable for this senior project applications</td>
</tr>
<tr>
<td>SEL Serial Connector</td>
<td>Connector for Relay</td>
<td>This special cable is necessary to communicate with the relay</td>
</tr>
</tbody>
</table>
Table 4 describes the necessary materials for this senior project. Different types of transformers and relays are required in this senior project to familiarize oneself with a diverse amount of equipment. Muti-tap current transformers are necessary in order to change the primary current to a suitable secondary current for the relay. The leads and connections must use the 14-gauge wire because it fits the rated ampacity of the relay. Lastly, only the SEL serial connector can be used to communicate from the computer terminal to the SEL relay.
Table 5 Marketing Requirements, Engineering Requirements, and Justifications

<table>
<thead>
<tr>
<th>Marketing Requirements</th>
<th>Engineering Requirements</th>
<th>Justifications</th>
</tr>
</thead>
</table>
| 1                      | 1. Relay settings must use the following transformer parameters:  
  • Transformer MVA  
  • Transformer Voltages (kV) | Protection design will only be applicable to transformers of these particular ratings and voltage levels |
| 1, 3                   | 2. Differential Relay must trip when currents polarities are flipped | Testing the differential relay is critical for transformer protection |
| 1, 2, 3                | 3. Relay must take in readings from each phase of the transformer and display them on the HMI. | Regardless of phase, if the transformer falls out of safe specifications, the relay must trip. |
| 1, 3                   | 4. Relay must be reprogrammable. | If testing fails, the user must be able to change the settings to meet the required protection specifications. |
| 2, 3                   | 5. If the differential relay trips, the event history must be stored and retrieved later for analysis | Diagnosing the cause of the trip is essential to determine the cause of the fault. |
| 1                      | 6. Device should be safe to install and use. | This product must keep the safety of its users in mind. The user must be able to operate the device without any risks to his/her health or safety. |

Marketing Requirements:  
1. Safe and easy to use  
2. Real Time Feedback  
3. Easy Diagnosis

Table 5 describes the marketing and engineering requirements for this design. Essentially, this protection design is safe and easy to use, provides real time feedback, and able to provide diagnosis in the form of a phasor diagram and oscillography to the engineer. These diagrams help engineers to analysis and determine the cause of the fault.
III. Design

4.1 Y-Y Transformer Protection

The project consists of the design and development of a protection system for three-single-phase 1 KVA 120:208 transformers configured in Δ-Δ, Y-Y, Y-Δ, and Δ-Y topologies. Figure 7 shows the YY connection. The SEL 387 relay reads the currents from the three-single-phase transformers via the Δ-Δ connected instrument current transformers. The current transformers must be connected in the opposite configuration as the main transformer to cancel out any 30 degree phase shifts that occur between a Δ and a Y connection. Furthermore, a load resistance of 35Ω provides a sufficient amount of current for the relay to operate in the case of a simulated fault as shown in the following:

\[
\frac{120}{35\Omega} \frac{[Load\ Current]}{10\ [CT\ Ratio]} = 0.343A
\]

The SEL 387 relay is then programmed by calculating the following: primary and secondary currents of the transformer, restrained element operating current, and overcurrent parameters as shown below:
**Primary Side (Low Voltage Side)**

\[ I_{primary} = \frac{3 \text{ MVA}}{\sqrt{3} \times 208 \text{ kV}_{\text{line to line-Y}}} = 8.3 \text{ A} \]

\[ I_{sec} = \frac{I_{primary}}{\text{CT Ratio}} = \frac{8.3 \text{ A}}{50/5} = 0.83 \text{ A} \]

\[ I_{relay} = I_{sec} \times \sqrt{3} = 0.83 \text{ A} \times \sqrt{3} = 1.44 \text{ A} \quad *\text{Note: } \sqrt{3} \text{ is due to the CT Connection (Δ)} \]

**Secondary Side (High Voltage Side)**

\[ I_{primary} = \frac{3 \text{ MVA}}{\sqrt{3} \times 360 \text{ kV}_{\text{line to line-Y}}} = 4.8 \text{ A} \]

\[ I_{sec} = \frac{I_{primary}}{\text{CT Ratio}} = \frac{4.8 \text{ A}}{50/5} = 0.48 \text{ A} \]

\[ I_{relay} = I_{sec} \times \sqrt{3} = 0.48 \text{ A} \times \sqrt{3} = 0.83 \text{ A} \quad *\text{Note: } \sqrt{3} \text{ is due to the CT Connection (Δ)} \]

**Restrained Element Operating Current**

Minimum Tap \(* 087P \geq 0.1 \times I_{\text{nominal}} \quad *\text{Note: 0.1 is the manufactured setting 10% [6]}

\[ 087P \geq \frac{0.1 \times I_{\text{nominal}}}{\text{Minimum Tap}} \quad *\text{Note: Minimum Tap is the lowest tap setting for the relay} \]

\[ 087P \geq \frac{0.1 \times 5 \text{ A}}{0.83 \text{ A}} \]

\[ 087P \geq 0.6 \text{ A} \]

**Overcurrent Relay**

Overcurrent Relay is placed on the primary side of the transformer

\[ I_{primary} = \frac{3 \text{ MVA}}{\sqrt{3} \times 208 \text{ kV}_{\text{line to line-Y}}} = 8.3 \text{ A} \]

Overcurrent Pick Up set for 250% of \( I_{\text{Full Load}} \)

\[ I_{\text{pickup primary}} = 2.5 \times 8.3 \text{ A} = 20.8 \text{ A} \]

\[ I_{\text{pickup relay}} = \frac{I_{\text{pickup primary}}}{\text{CT Ratio}} \times \sqrt{3} = \frac{20.8}{50/5} \times \sqrt{3} = 3.6 \text{ A} \quad *\text{Note: } \sqrt{3} \text{ is for the CT Connection (Δ)} \]

\[ I_{\text{relay}} = \frac{V_{\text{p.u.}}}{Z_{\text{p.u.}}} = \frac{1.0 \text{ p.u.}}{Z_{\text{system}} + Z_{\text{transformer}}} = \frac{1.0 \text{ p.u.}}{0+0.1} = 10 \text{ p.u.} \]

*Note: Z-system is assumed zero and Z-transformer assumed to be 10% impedance

\[ I_{\text{relay}} = l \text{ p.u.} \times I_{\text{base}} = 10 \text{ p.u.} \times 8.3 \text{ A} = 83 \text{ A} \]
\[ I_{\text{base}} = \frac{3 \text{ MVA}}{\sqrt{3} \times 208 \text{ kV}_{\text{line to line}}} = 8.3 \text{ A} \]

\[ I_{\text{Fault}} = 83 \text{ A} \]

\[ I_{\text{secondary}} = \frac{I_{\text{Fault}}}{\text{CT Ratio}} = \frac{83 \text{ A}}{50/5} = 8.3 \text{ A} \]

\[ I_{\text{Relay}} = 8.3 \text{ A} \times \sqrt{3} = 14.38 \text{ A} \]

\[ \text{Multiply Tap} = \frac{I_{\text{Relay}}}{I_{\text{pickup Relay}}} = \frac{14.38 \text{ A}}{3.6 \text{ A}} = 4 \text{ times} \]

*Time Delay assumed to be 30 cycles ~ 0.5 Seconds and using U3 Curve*

\[ T_{\text{operating}} = T_{\text{Index}} \times (0.0963 + \frac{3.88}{M^2 - 1}) \]

\[ T_{\text{Index}} = \frac{0.5}{(0.0963 + \frac{3.88}{4^2 - 1})} = 1.4 \]

The restraining element of the relay allows for the currents entering and exiting the relay to be unequal. For example, the calculations for the secondary relay currents are respectively 1.44 A and 0.83 A. Even though these currents differ by 0.61 A, the restraining element does not allow the relay to trip under normal conditions.

### Table 6 Primary/Secondary CT Ratio and Primary/Secondary Line Current for YY, DD, YD, DY Configurations

<table>
<thead>
<tr>
<th></th>
<th>CT Ratio Primary</th>
<th>CT Ratio Secondary</th>
<th>Primary Line Current [A]</th>
<th>Secondary Line Current [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>YY</td>
<td>10</td>
<td>10</td>
<td>8.3</td>
<td>4.8</td>
</tr>
<tr>
<td>DD</td>
<td>10</td>
<td>10</td>
<td>14.43</td>
<td>8.33</td>
</tr>
<tr>
<td>YD</td>
<td>10</td>
<td>4</td>
<td>8.33</td>
<td>8.33</td>
</tr>
<tr>
<td>DY</td>
<td>10</td>
<td>10</td>
<td>14.43</td>
<td>4.8</td>
</tr>
</tbody>
</table>

### Table 7 Primary/Secondary Relay Current and Restrained Element for YY, DD, YD, DY Configurations

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.44</td>
<td>0.83</td>
<td>0.6</td>
</tr>
<tr>
<td>1.44</td>
<td>0.83</td>
<td>0.6</td>
</tr>
<tr>
<td>1.438</td>
<td>2.075</td>
<td>0.6</td>
</tr>
<tr>
<td>1.44</td>
<td>0.83</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Table 8 SEL Overcurrent Parameters for YY, DD, YD, DY Configurations

<table>
<thead>
<tr>
<th>Primary Pickup Current [A]</th>
<th>Relay Fault Current [A]</th>
<th>Multiply of Taps</th>
<th>$T_{index}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6</td>
<td>14.38</td>
<td>4</td>
<td>1.4</td>
</tr>
<tr>
<td>3.6</td>
<td>14.38</td>
<td>4</td>
<td>1.4</td>
</tr>
<tr>
<td>3.6</td>
<td>14.38</td>
<td>4</td>
<td>1.4</td>
</tr>
<tr>
<td>3.6</td>
<td>14.38</td>
<td>4</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Table 9 Enable Winding Element for YY, DD, YD, DY Transformer Configurations

<table>
<thead>
<tr>
<th>E87W1</th>
<th>E87W2</th>
<th>E87W3</th>
<th>E87W4</th>
</tr>
</thead>
<tbody>
<tr>
<td>YY</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>DD</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>YD</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>DY</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
</tbody>
</table>

Table 10 Enable Overcurrent Elements and CT Configurations for YY, DD, YD, DY Transformer Configurations

<table>
<thead>
<tr>
<th>EOC1</th>
<th>EOC2</th>
<th>W1CT</th>
<th>W2CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>N</td>
<td>Δ</td>
<td>Δ</td>
</tr>
<tr>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Δ</td>
</tr>
<tr>
<td>Y</td>
<td>N</td>
<td>Δ</td>
<td>Y</td>
</tr>
<tr>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Δ</td>
</tr>
</tbody>
</table>

Table 11 CT Ratios, Power Rating, Primary/Secondary Voltage for YY, DD, YD, DY Transformer Configurations

<table>
<thead>
<tr>
<th>CTR1</th>
<th>CTR2</th>
<th>MVA</th>
<th>VWDG1</th>
<th>VWDG2</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10</td>
<td>3</td>
<td>120 kV</td>
<td>208 kV</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>3</td>
<td>120 kV</td>
<td>208 kV</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>3</td>
<td>120 kV</td>
<td>208 kV</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>3</td>
<td>120 kV</td>
<td>208 kV</td>
</tr>
</tbody>
</table>

Table 12 Differential TAP settings, Operating Current, CT Slope Percentage, and for YY, DD, YD, DY Transformer Configurations

<table>
<thead>
<tr>
<th>TAP1</th>
<th>TAP2</th>
<th>087P</th>
<th>SLP1</th>
<th>SLP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.44</td>
<td>0.83</td>
<td>0.61</td>
<td>25%</td>
<td>50%</td>
</tr>
<tr>
<td>1.44</td>
<td>0.83</td>
<td>0.61</td>
<td>25%</td>
<td>50%</td>
</tr>
<tr>
<td>1.438</td>
<td>2.075</td>
<td>0.61</td>
<td>25%</td>
<td>50%</td>
</tr>
<tr>
<td>1.44</td>
<td>0.83</td>
<td>0.61</td>
<td>25%</td>
<td>50%</td>
</tr>
</tbody>
</table>
Table 13 Phase Inverse Time Overcurrent Curve, Time Dial, Torque Control, Trip Logic, Output Contant Logic for YY, DD, YD, DY Transformer Configurations

<table>
<thead>
<tr>
<th>51P1C</th>
<th>51P1TD</th>
<th>51P1TC</th>
<th>TRIP LOGIC</th>
<th>Output Contact Logic</th>
</tr>
</thead>
<tbody>
<tr>
<td>U3</td>
<td>1.4</td>
<td>Y</td>
<td>51P1T + 87R + 87U</td>
<td>Trip1</td>
</tr>
<tr>
<td>U3</td>
<td>1.4</td>
<td>Y</td>
<td>51P1T + 87R + 87U</td>
<td>Trip1</td>
</tr>
<tr>
<td>U3</td>
<td>1.4</td>
<td>Y</td>
<td>51P1T + 87R + 87U</td>
<td>Trip2</td>
</tr>
<tr>
<td>U3</td>
<td>1.4</td>
<td>Y</td>
<td>51P1T + 87R + 87U</td>
<td>Trip3</td>
</tr>
</tbody>
</table>

Table 6 through 8 display the differential relay calculations for the YY, DD, YD, DY transformer configurations.

Table 9 through 13 display the inputs to AcSELerator QuickSet program. As shown in the SEL 387 relay inputs the winding voltages and power ratings are inputted in KV and MVA. This is because the relay does not allow voltage ratings below 1 KV and power ratings below 0.2 MVA. In order to use this relay, the values were inputted in KV and MVA instead of the calculated V and KVA values. In the math, the currents ended up matching with what was calculated as shown in the following:

\[
I_{primary} = \frac{3 \text{ MVA}}{\sqrt{3} \times 208 \text{ kV line to line - Y}} = 8.3 \text{ A}
\]

\[
I_{primary} = \frac{3 \text{ kVA}}{\sqrt{3} \times 208 \text{ V line to line - Y}} = 8.3 \text{ A}
\]

Also, note that the settings for the Y-∆ configuration are different from the rest. This is because the original CT ratio of 10 on the secondary side did not provide enough current to the relay to operate. As a result, the CT ratio had to be changed from 10 to 4.

See Appendix for the Design of SEL 587 Laboratory.
IV. Development and Construction

5.1 Project Overview

The protection design of the 3-Single Phase Transformers is broken up in three steps. The first step is making the correct transformer primary and secondary connections. In the second step, relay calculation are made and uploaded to the SEL 387 relay. Lastly, the relay is tested with the method in the testing procedure. The same protection design is implemented for SEL 587; however, the only transformer connection that will be test is the YY configuration and instead of the 3-Single Phase Transformers, 120:208 it is now 3-Single Phase Transformers 240:120.

5.2 Project Timeline

A Gantt chart was created to provide a rough timeline for the design, construction, and testing of the project. The Gantt chart is provided in the appendix, however due to many changes throughout the life of the project, the chart tasks are inaccurate or no longer relevant to the project. Additionally, the scheduled outlined in the chart was loosely followed, as the project timeline was significantly modified throughout the development process.
5.3 Transformer and Current Transformer Assembly

The transformer connections are made with the 14-gauge wire to form the appropriate configurations (Δ-Δ, Y-Y, Y-Δ, and Δ-Y). Spades were added to the ends of the wire to make it easier to connect and disconnect from the relay terminals for testing. To connect the CTs to the relay, the ends of the terminals have to be tied together. For example, for a Y-Δ configured transformer, requires a Δ configured CTs on the primary side and a Y configured CTs on the secondary side as shown in Figure 8.

Figure 8 Delta-Y Transformer with CT Configuration [5]
Figure 9 Current Transformer Connection on Source Side

Figure 10 Current Transformer Connection on Load Side
Figure 9 and Figure 10 give a system representation on how the connections should be made for a Δ-Y transformer for the first phase of the senior project. As mentioned in the design section, the reason why the CTs configuration are in the opposite configuration to the power transformer is so that the 30 degree phase shift is canceled out.
V. Testing Procedure

During the testing phase, the differential relay will be the only relay tested in the design. Even though the overcurrent relay is implemented in the protection design, it cannot be tested due to the limitations of the power equipment available. The first test is to make sure to energize the transformer under normal conditions. Once energized, the event report of the relay should output an oscillography that has all the winding currents out of 180 degrees out of phase. In addition, the phasors of each individual winding are also 180 degrees out of phase.

Figure 11 Oscillography of Normal Operation
Figure 11 and Figure 12 show the oscillography and the phasor diagram of a normal operating transformer. As seen in Figure 11, for phase A windings 1 and 2, each of the waveforms are 180 degrees out of phase indicating that the current is entering the relay and exiting the relay as designed. Figure 12, also displays the same phenomenon with each winding entering and exiting the relay as designed.

In order to test the differential relay, the current’s polarities are physically flipped by switching the leads of winding 1 (polarity) with winding 1 (non-polarity). Figure 13 shows how to physically flip a winding polarity.
Figure 13 Relay Connections to SEL 387 Relay

Figure 13, displays how a three-phase fault is simulated. By swapping each wire from their respective winding terminals, causes the currents to flow a opposite direction effectively flipping the polarity of the current. When the polarity is flipped, an internal fault is simulated on either the primary or the secondary side of the transformer depending on which winding is flipped. For example, if IAW1 wires are swapped with each other, a simulated fault occurs on the A-phase (primary side).
Table 14 Simulated Faults applied to Transformer

<table>
<thead>
<tr>
<th>Simulated Faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Line To Ground Fault A Phase</td>
</tr>
<tr>
<td>Single Line To Ground Fault B Phase</td>
</tr>
<tr>
<td>Single Line To Ground Fault C Phase</td>
</tr>
<tr>
<td>Double Line to Ground Fault A Phase and B Phase</td>
</tr>
<tr>
<td>Double Line to Ground Fault A Phase and C Phase</td>
</tr>
<tr>
<td>Double Line to Ground Fault B Phase and C Phase</td>
</tr>
<tr>
<td>Three Phase Fault</td>
</tr>
</tbody>
</table>

Table 14 displays the faults applied to each 3-phase transformer connection (Y-Y, Δ-Δ, Y-Δ, and Δ-Y). Once each of these faults is applied to the transformer, an event report is generated by the SEL relay. In order to verify that the test is successful, the event report must display the correct characteristics as shown below:

![Oscillography of A Phase Fault Winding 1 Source Side](image)

**Figure 14 Oscillography of A Phase Fault Winding 1 Source Side**

In the event report generated by the SEL relay, the oscillography displays the result for a fault on A-phase Winding 1 Source Side as shown in Figure 14. In the circle, A-phase Winding 1 and Winding 2
are in phase, this means that the currents for the differential relay are adding up, causing the relay to trip.

![Figure 15 Verification that Phase A Winding 1 and 2 are aligned](image)

Also in the event report, the SEL relay outputs a phasor diagram as shown in Figure 15. Like the oscillography shown in Figure 14, the phasor diagram also shows that A-phase Winding 1 and Winding 2 are in phase with each other. Even though these windings are not completely aligned due to the quality of the CTs, the relay will still trip for this case.
VI. Analysis

As a full system protection design, testing was performed on each three-phase transformer connection YY, DY, YD, DD configurations for the SEL 387 and SEL 587 relay. Only the differential relay was tested as described in the testing procedure; the details of the SEL 387 are shown below.

7.1 ∆-Y Transformer Configuration Test

In Figure 16, the ∆-Y transformer configuration was tested by flipping the polarities on the secondary windings of the relay. Unfortunately, for this particular test the relay constantly tripped due to the quality of the CT. As a result, CT compensation was used on the secondary winding of the relay as shown in Figure 17.
When using CT compensation, the value of each number (1-12) indicates the number of 30 degree phase shifts added to the phasor. In this case, winding 2 needed a CT compensation of 30 degrees to make this setup work.

See Appendix for oscillography and phasor diagrams of other transformer configurations.
VII. Conclusion

Overall, this project was a success; all major design goals were met at the time of project completion. The finished protection design consists of an SEL relay that utilizes differential protection to monitor and sense internal faults in a transformer for ∆-∆, Y-Y, Y-∆, and ∆-Y topologies. The protection design passed all major tests for accuracy and overall functionality. Lastly, a laboratory manual utilizing a SEL 587 relay to protect a Y-Y configured transformer was also completed at the project deadline. The manual implemented the same protection design as described in the first part of this project and all the requirements were met.

However, although all major protection design goals were met, there are many areas for future improvement and refinement. If multiple circuit breakers were provided, the protection design could have used them to isolate the transformer from the system. By implementing circuit breakers in the overall protection design, the overcurrent element could have been fully tested. Additionally, performance of the overall protection system can be improved with better current transformers. With better CTs, the phasor diagrams and oscillography will display the currents to be exactly 180 degrees out of phase thus depicting a healthy radial transformer.

The skills learned in the power protection system engineering courses were used during the design stage of this project. The construction and testing process provided good experience in protection design and real-real power system engineering. The final product of this project not only provided a protection design and a lab manual for future EE 444 students, but also built a good foundation to use SEL relays on other power system related applications.
## VIII. Appendices

### Gant Chart

<table>
<thead>
<tr>
<th>Task</th>
<th>Start Date</th>
<th>Duration</th>
<th>End Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Development</td>
<td>24-Sep-12</td>
<td>7</td>
<td>1-Oct-12</td>
</tr>
<tr>
<td>Proposal</td>
<td>1-Oct-12</td>
<td>49</td>
<td>19-Nov-12</td>
</tr>
<tr>
<td>Obtain Parts</td>
<td>19-Nov-12</td>
<td>60</td>
<td>18-Jan-13</td>
</tr>
<tr>
<td>First Design</td>
<td>18-Jan-13</td>
<td>14</td>
<td>1-Feb-13</td>
</tr>
<tr>
<td>Prototype Build</td>
<td>1-Feb-13</td>
<td>14</td>
<td>15-Feb-13</td>
</tr>
<tr>
<td>Test Design</td>
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<td>1-Mar-13</td>
<td>14</td>
<td>15-Mar-13</td>
</tr>
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<td>Final Build</td>
<td>15-Mar-13</td>
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<td>29-Mar-13</td>
</tr>
<tr>
<td>Test Design</td>
<td>29-Mar-13</td>
<td>14</td>
<td>12-Apr-13</td>
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<td>Interim Report</td>
<td>11-Apr-13</td>
<td>1</td>
<td>12-Apr-13</td>
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<tr>
<td>Final Verification/Adj.</td>
<td>12-Apr-13</td>
<td>28</td>
<td>10-May-13</td>
</tr>
<tr>
<td>Final Report</td>
<td>10-May-13</td>
<td>22</td>
<td>1-Jun-13</td>
</tr>
<tr>
<td>Senior Project Expo</td>
<td>29-May-13</td>
<td>1</td>
<td>30-May-13</td>
</tr>
</tbody>
</table>
YY Configuration Event Report

A Phase and B Phase Fault Winding 1 (Source)
A Phase and B Phase Fault Winding 2 (Load)
A Phase Fault Winding 1 (Source)
A Phase Fault Winding 2 (Load)
A Phase and C Phase Fault Winding 1 (Source)
A Phase and C Phase Fault Winding 2 (Load)
B Phase and C Phase Fault Winding 1 (Source)
B Phase and C Phase Fault Winding 2 (Load)
B Phase Fault Winding 1 (Source)
B Phase Fault Winding 2 (Load)
C Phase Fault Winding 1 (Source)
C Phase Fault Winding 2 (Load)
Three Phase Fault Winding 1 (Source)
Three Phase Fault Winding 2 (Load)
Δ-Δ Configuration Event Report

A Phase and B Phase Fault Winding 1 (Source)
A Phase and B Phase Fault Winding 2 (Load)
A Phase Fault Winding 1 (Source)
A Phase Fault Winding 2 (Load)
A Phase and C Phase Fault Winding 1 (Source)
A Phase and C Phase Fault Winding 2 (Load)
B Phase and C Phase Fault Winding 1 (Source)
B Phase and C Phase Fault Winding 2 (Load)
B Phase Fault Winding 1 (Source)
C Phase Fault Winding 1 (Source)
C Phase Fault Winding 2 (Load)
Three Phase Winding 1 (Source)

Graph for [Diagram Image]

- IAW1, IAW2, IBW1, IBW2, ICW1, ICW2
- Cycles from 2.5 to 15.0

Phase Diagram for [Diagram Image]

- Data Selection
- Auto Increment
- Start: 0
- End: 360
- Increment: 10
- Phases: IAW1, IAW2, IBW1, IBW2, ICW1, ICW2
- IW11, IW22
Three Phase Winding 2 (Load)
Δ-Y Configuration Event Report

A Phase and B Phase Fault Winding 1 (Source)
A Phase and B Phase Fault Winding 2 (Load)
A Phase and C phase Fault Winding 1 (Source)
A Phase and C Phase Fault Winding 2 (Load)
A Phase Fault Winding 1 (Source)
A Phase Fault Winding 2 (Load)
B Phase Fault Winding 1 (Source)
B phase Fault Winding 2 (Load)
C Phase Fault Winding 1 (Source)
C Phase Fault Winding 2 (Load)
Three Phase Winding 1 (Source)
Three Phase Winding 2 (Load)
Y-Δ Configuration Event Report

Phase A and Phase B Fault Winding 1 (Source)
Phase A and Phase B Fault Winding 1 (Load)
Phase A and Phase C Fault Winding 1 (Source)
Phase A and Phase C Fault Winding 2 (Load)
A Phase Fault Winding 1 (Source)
A Phase Fault Winding 2 (Load)
Phase B and Phase C Fault Winding 1 (Source)
Phase B and Phase C Fault Winding 2 (Load)
B Phase Winding 1 (Source)
C Phase Fault Winding 1 (Source)
C Phase Fault Winding 2 (Load)
Three Phase Fault Winding 1 (Source)
Design for SEL 587 Lab

Figure 18 Three Single Phase Transformers Y-Y and Δ CT Configurations with SEL 587 Relay

For the second phase of the project consists of utilizing the same setup as the first phase of the project, but with the SEL 587 relay, three single-phase transformers 240:120, and 17.5Ω Y-connected loads. Due to the three-hour time constraint of Cal Poly labs, only the YY configuration transformer connection will be implemented as shown in Figure 18.

Similar to the SEL 387 relay, the SEL 587 is then programmed by calculating the following: primary and secondary currents of the transformer, restrained element operating current, and overcurrent parameters as shown below:

**Primary Side (High Voltage Side)**

\[
I_{\text{primary}} = \frac{3 \text{ MVA}}{\sqrt{3} \times 416 \text{ kV}_{\text{line to line}} - \text{Y}} = 4.17 \text{ A}
\]

\[
I_{\text{sec}} = \frac{I_{\text{primary}}}{\text{CT Ratio}} = \frac{4.17 \text{ A}}{50/5} = 0.417 \text{ A}
\]

\[
I_{\text{relay}} = I_{\text{sec}} \times \sqrt{3} = 0.417A \times \sqrt{3} = 0.723 \text{ A} \quad \text{*Note: } \sqrt{3} \text{ is due to the CT Ratio configuration~Δ}
\]

**Secondary Side (Low Voltage Side)**
\[ I_{primary} = \frac{3 \text{ MVA}}{\sqrt{3} \times 208 \text{ kV}_{\text{line to line}}} = 8.3 \text{ A} \]

\[ I_{sec} = \frac{I_{primary}}{\text{CT Ratio}} = \frac{8.33 \text{ A}}{50/5} = 0.83 \text{ A} \]

\[ I_{relay} = I_{sec} \times \sqrt{3} = 0.83 \text{ A} \times \sqrt{3} = 1.44 \text{ A} \]

*Note: \( \sqrt{3} \) is due to the CT Ratio configuration\(- \Delta \).

**Restrained Element Operating Current**

Minimum Tap * 087P ≥ 0.1 * \( I_{nominal} \) *Note: 0.1 is the manufactured setting 10% [6]

\[ 087P \geq \frac{0.1 \times I_{nominal}}{\text{Minimum Tap}} \]

*Note: Minimum Tap is the lowest tap setting for the relay

\[ 087P \geq \frac{0.1 \times 5 \text{ A}}{0.83 \text{ A}} \]

\[ 087P \geq 0.6 \text{ A} \]

**Overcurrent Relay**

Overcurrent Relay is placed on the primary side of the transformer

\[ I_{primary} = \frac{3 \text{ MVA}}{\sqrt{3} \times 416 \text{ kV}_{\text{line to line}}} = 4.17 \text{ A} \]

Overcurrent Pick Up set for 250% of \( I_{Full \text{ Load}} \)

\[ I_{pickup \text{ primary}} = 2.5 \times 4.17 \text{ A} = 10.425 \text{ A} \]

\[ I_{pickup \text{ relay}} = \frac{I_{pickup \text{ primary}}}{\text{CT Ratio}} \times \sqrt{3} = \frac{10.425}{50/5} \times \sqrt{3} = 1.814 \text{ A} \]

*Note: \( \sqrt{3} \) is for the CT Configuration

\[ I_{3-\phi} = \frac{V_{p.u.}}{Z_{p.u.}} = \frac{1.0 \text{ p.u.}}{Z_{\text{system}} + Z_{\text{transformer}}} = \frac{1.0 \text{ p.u.}}{0+0.1} = 10 \text{ p.u.} \]

*Note: Z-system is assumed zero and Z-transformer assumed to be 10% impedance

\[ I_{3-\phi} = l \text{ p.u.} \times I_{Base} = 10 \text{ p.u.} \times 4.27 \text{ A} = 42.7 \text{ A} \]

\[ I_{Base} = \frac{3 \text{ MVA}}{\sqrt{3} \times 416 \text{ kV}_{\text{line to line}}} = 4.17 \text{ A} \]

\[ I_{Fault} = 42.7 \text{ A} \]

\[ I_{secondary} = \frac{I_{Fault}}{\text{CT Ratio}} = \frac{42.7 \text{ A}}{50/5} = 4.27 \text{ A} \]

\[ I_{Relay} = 4.27 \text{ A} \times \sqrt{3} = 7.4 \text{ A} \]
Multiply Tap = \( \frac{I_{\text{Relay}}}{I_{\text{pickup Relay}}} = \frac{7.4 \text{ A}}{1.81 \text{ A}} = 4 \text{ times} \)

*Time Delay assumed to be 30 cycles ~ 0.5 Seconds and using U3 Curve

\[ T_{\text{operating}} = T_{\text{Index}} \times (0.0963 + \frac{3.88}{M^2 - 1}) \]

\[ T_{\text{Index}} = \frac{0.5}{(0.0963 + \frac{3.88}{4^2 - 1})} = 1.4 \]

Table 15 SEL 587 Relay Inputs for YY Connection

<table>
<thead>
<tr>
<th>MVA</th>
<th>VWDG1</th>
<th>VWDG2</th>
<th>TRCON</th>
<th>CTCON CT Connection</th>
<th>CTR1</th>
<th>CTR2</th>
<th>TAP1</th>
<th>TAP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>416 KV</td>
<td>208 KV</td>
<td>YY</td>
<td>DABDAB</td>
<td>10</td>
<td>10</td>
<td>0.72 A</td>
<td>1.44 A</td>
</tr>
</tbody>
</table>

Table 16 SEL 587 Relay Inputs for YY Connection (Continued)

<table>
<thead>
<tr>
<th>IN1</th>
<th>IN2</th>
<th>087P</th>
<th>TH5</th>
<th>51P1P</th>
<th>51P1C</th>
<th>51P1TD</th>
<th>51P1RS</th>
<th>PHROT</th>
<th>X (SELogic Equation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td>N/A</td>
<td>0.7</td>
<td>0.7</td>
<td>1.81</td>
<td>U3</td>
<td>1.4</td>
<td>Y</td>
<td>ACB</td>
<td>51P1T + 87R + 87U</td>
</tr>
</tbody>
</table>

Similar to the SEL 387 relay, Table 15 and Table 16 display relay inputs into the SEL 587 relay.
Transformer Differential Protection Lab Manual

Objective

To teach students how to set up differential protection on an YY transformer with delta configured current transformers. In addition, to learn how to test the differential protection as well as become familiar with SEL QuickSet and AcSELerator Analytic Assistant programs.

Equipment

- SEL-587 Relay
- Single Phase Transformer, 240/120 V, 3 KVA (3)
- (6) Resistive Load 35 Ω
- (6) General electric JP-1 Instrument Current Transformer
- Banana to Banana Leads
- Spade to Spade Leads
- Banana to Spade Leads

Procedure

1. Configure the circuit as shown in Figure 19. Connect current transformers for the source and load side of the main transformer:
   a. Refer to the current transformer diagram in Figure 20

![Figure 19 Three Single Phase Transformers Y-Y and Delta CT Configurations](image_url)
Figure 20 50:5 CT Diagram

Positive Dotted High Side of Current Transformer

Negative Undotted High Side of Current Transformer

Positive Secondary Side of Current Transformer

Negative Secondary Side of Current Transformer
b. Connect the current transformers in the delta configuration and terminate the windings as shown in Figure 21.

![Figure 21 Wiring Diagram for CTs](image1)

C. Connect the current transformers on the source side as shown in Figure 22.

![Figure 22 Current Transformer Connection on Source Side](image2)
d. Refer to Figure 23 for visual current transformer connection on the source side.

Figure 23 Actual Wiring Delta Configuration of the Current Transformers for Winding 1

- This side of the CT connects to Winding 1 Terminal A
- This side of the CT connects to Winding 1 Terminal B
- This side of the CT connects to Winding 1 Terminal C

Note that this side of the CT is connected in DELTA
e. Connect the current transformer on the load side as shown in Figure 24.

Figure 24 Current Transformer Connection on Load Side
Refer to Figure 25 for visual current transformer connection on the source side.

Figure 25 Actual Wiring Delta Configuration of the Current Transformers for Winding 2

Note that this side of the CT is connected in DELTA.
g. Terminate the windings as shown in Figure 21. Again, this termination allows current to flow throughout the winding.

2. Connect the 17.5Ω resistor to each phase of the transformer as shown in Figure 24.

3. Connect the computer to the relay.
   a. Check the “port settings” by using the HDMI display on the relay: (SET-PORT-SHOW).
   b. Open SEL QuickSet and input the same parameters from “port settings” into the relay. Additionally, the level one password: 587 and the level two password is Otter.
4. Calculate the necessary parameters for setting the 587 relay as shown below:

**Primary Side**

*Note: * is due to the CT Ratio configuration—Delta

<table>
<thead>
<tr>
<th>Restrained Element Operating Current</th>
<th>100</th>
</tr>
</thead>
</table>

**Secondary Side**

*Note: * is due to the CT Ratio configuration—Delta

**Restrained Element Operating Current**
Minimum Tap * O87P ≥ 0.1 * I_{nominal} *Note: 0.1 is the manufactured setting 10%

\[ O87P \geq \frac{0.1 \cdot I_{nominal}}{\text{Minimum Tap}} \] *Note: Minimum Tap is the lowest tap setting for the relay

\[ O87P \geq \frac{0.1 \cdot 5A}{0.83A} \]

\[ O87P \geq 0.6A \] *Choose 0.7 for O87P

**Overcurrent Relay**

Overcurrent Relay is placed on the primary side of the transformer

\[ I_{primary} = \frac{3 \text{ MVA}}{\sqrt{3} \cdot 416 \text{ kV}_{line to line}} = 4.17A \]

Overcurrent Pick Up set for 250% of \( I_{Full \ Load} \)

\[ I_{pickup \ primary} = 2.5 \cdot 4.17A = 10.425A \]

\[ I_{pickup \ Relay} = \frac{I_{pickup \ primary}}{\text{CT Ratio}} \cdot \sqrt{3} = \frac{10.425}{5/5} \cdot \sqrt{3} = 1.81A \] *Note: \( \sqrt{3} \) is for the CT Configuration

\[ I_{3-\varphi} = \frac{V_{p.u.}}{Z_{p.u.}} \cdot \frac{1.0 \ p.u.}{Z_{system} + Z_{transformer}} = \frac{1.0 \ p.u.}{0+0.1} = 10 \ p.u. \]

*Note: Z-system is assumed zero and Z-transformer assumed to be 10% impedance

\[ I_{3-\varphi} = I_{p.u.} \cdot I_{base} = 10 \ p.u. \cdot 4.27A = 42.7A \]

\[ I_{base} = \frac{3 \text{ MVA}}{\sqrt{3} \cdot 416 \text{ kV}_{line to line}} = 4.17A \]

\[ I_{Fault} = 42.7A \]

\[ I_{secondary} = \frac{I_{Fault}}{\text{CT Ratio}} = \frac{42.7A}{50/5} = 4.27A \]

\[ I_{Relay} = 4.27A \cdot \sqrt{3} = 7.4A \]

\[ \text{Multiply Tap} = \frac{I_{Relay}}{I_{pickup \ Relay}} = \frac{7.4A}{1.81A} = 4 \text{ times} \]

*Time Delay assumed to be 30 cycles ~ 0.5 Seconds and using U3 Curve

\[ T_{operating} = T_{Index} \cdot (0.0963 + \frac{3.88}{M^2 - 1}) \]
\[ T_{\text{index}} = \frac{0.5}{\left(0.0963 + \frac{3.88}{4^2 - 1}\right)} = 1.4 \]

5. Program the relay with the calculated values.
   a. Create a new settings file and select 587-1 version 1 as shown in Figure 28.

![Figure 28 Settings Editor Selection for SEL-587-1](image1)

b. Insert the same device parameters as shown in Figure 29.

![Figure 29 Device Part Number for 587](image2)

c. Insert the following parameters into the relay settings page

**General Data**

- MVA= 3 MVA *Does not have a setting for KVA
- VWDG1=416 kV *Line to Line voltage of Primary
- VWDG2=208 kV
- TRCON Xfmr= YY
- CTCON CT Connection= DABDAB
CTR1=50/5=10
CTR2=10

Current Taps
TAP1= 0.72 A
TAP2=1.44 A

Input Assignment
IN1 Input 1= NA
IN2 Input 2= NA

Differential Elements
087P=0.7
TH5=0.7

Winding 1 Overcurrent
51P1P=1.81 *Minimum Pickup
51P1C=U3 *Curve that we will be using
51P1TD=1.4
51P1RS=Y *Reset

PWR System Data
PHROT: ACB ~This is how PG&E defines their phase rotation.

SELogic Settings
X (SELogic Equation) = 51P1T + 87R + 87U
MTU1 (SELogic Equation) = 51P1T+87R+87U
d. Verify your settings with the instructor. Click on “send active settings” on the QuickSet toolbar.

Testing
1. To test differential relay flip the polarities on the following phases:
Table 17 Faults to test

<table>
<thead>
<tr>
<th>Simulated Faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Line To Ground Fault A Phase</td>
</tr>
<tr>
<td>Single Line To Ground Fault B Phase</td>
</tr>
<tr>
<td>Single Line To Ground Fault C Phase</td>
</tr>
<tr>
<td>Double Line to Ground Fault A Phase and B Phase</td>
</tr>
<tr>
<td>Double Line to Ground Fault A Phase and C Phase</td>
</tr>
<tr>
<td>Double Line to Ground Fault B Phase and C Phase</td>
</tr>
<tr>
<td>Three Phase Fault</td>
</tr>
</tbody>
</table>

Table 17 describes what faults will be tested in this experiment. Flipping the polarities on winding represents a fault inside the transformer. For example, when the polarity is flipped on phase A of winding 1, the differential relay will trip for a fault on phase A. The same process is applied to the relay when testing a fault on two or three phases. Since the differential relay is independent of each phase, the relay will trip only for the phases with a flipped polarity.

Figure 30 Example of which set of phases to flip
Figure 30 gives a visual representation of what polarities to flip to test the differential relay.

2. Turn on the transformer after each test and verify that the relay has tripped. **Turn off the transformer after 10 seconds (This is to insure that you are able to get enough data).** Once tripped, read event report from the QuickSet program.

Select “view event files” and you can retrieve the event you want by selecting “get selected events.” Record this in your report and reset the targets on your relay. Repeat this step for every test in table 1.

Analysis

1. Open .cev file for single phase A on winding 1 and AcSELerator Analytic Assistant program should open. Select preferences and select A-phase winding 1 and 2 to axis 1, B phase winding 1 and 2 to axis 2, and C phase winding 1 and 2 to axis 3. Delete all other phase windings and select “Okay”.
2. Verify that phase A winding 1 and winding 2 are in phase. When these waveforms are in phase with each other, this means that the currents are in opposite directions. Verify that the relay has tripped only on phase A.

Ignore the few cycles in the beginning due to transients and the red circle points out that the current waveforms of windings 1 and 2 on phase A are in phase with each other.

3. Open the phasor application on the AcSEIerator Analytic tool.
4. Go to the end of 15 cycles and verify that both A-Phases are aligned.

5. Repeat these for all cases and include these oscillography and phasor diagrams in your lab report.
References

IEEE Articles

   - Provides information on how transformers are protected by utilizing differential and overcurrent relays. This source is legitimate because its and IEEE article.

2. SEL, Protecting Power Systems for Engineers, 2007
   - This text provides information on how to protect transformers and other power apparatuses. This source has authority because it is a manufacturer of electrical protective equipment.

Books

   - EE-406 Book that provides background information of how to use differential and overcurrent relays. In addition, gives good information on how the Power System Works. This source is legitimate because this book is used to teach Power System Analysis at Cal Poly San Luis Obispo.

   - Provides information about Power System Protection to help understand the properties that relays use to protect the system. Professor Shaban recommended this book.

5. A. Shaban, EE 518 Slides, 2013
   - Provides information about Power System Protection. Professor Shaban provided these slides.

Datasheets

   - Datasheet for the SEL 387 Relay and it is essential to be able to use the device in this senior project. This source has authority because it is the manufacturer of the protective equipment.

7. SEL, SEL 587 Current Differential Relay Datasheet, 2010
   - Datasheet for the SEL 587 Relay and it is essential to be able to use the device in this senior project. This source has authority because it is the manufacturer of the protective equipment.

8. Westinghouse, Types HU and HU-1 Transformer Differential Relays, 1961
   - This source provided information regarding electromechanical relays. This source has authority because it is a manufacturer of the electrical protective equipment.

Websites

   - Source provided graphics on how to set up differential relays. This source has authority because from prior experience, the information is valid.

- Source provided information on the differences of electromechanical and microprocessor relays. Valid because sources on the website are sited and due to prior experience, the information is valid.