SETTING THE SEL-387 MICROPROCESSOR
BASED RELAY

Electrical Engineering 490C Term Project
Submitted to Dr. B. Mork

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Last minute project.
Scope is quite small,
compared to other groups
who started in time.
(4.5 weeks were available to work)

7.5/10
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Introduction

The purpose of this lab was to design the protective relaying scheme used for a three-phase 345:140 kV transformer used by Consumers Energy. In designing this scheme, we used the SEL-387 microprocessor based current differential relay. This relay is the same relay used by Consumers Energy for their transformer protection schemes.

Another objective of this lab was to learn how to use the specifications of equipment to design the needed protection for that piece of equipment. This will further our understanding of protective relay engineering.

Background

The three-phase transformer is a vital piece of our power grid. It connects all of the high voltage power lines to the lower voltage that customers need. It also connects the lower voltage power generating stations to the high voltage, power transmission lines. Therefore, transformers need to be in service all of the time in order to maintain the power flowing to the customer.

To keep this transformer in constant use, relays are needed to monitor the voltage and current levels in the transformer and then trip a circuit breaker if these levels become unsafe for operation. Safe operation includes; not operating while the current level is above rated, not operating when the oil level is too low to cool the transformer, not operating when the internal temperature is above rated temperature, and not allowing the transformer to operate during an internal fault.

Another reason for protective relays on a transformer is the economic standpoint. Transformers are one of the most expensive individual pieces of equipment in the power system. A typical 345:138 kV, 300/400/500 MVA, load tap changing transformer can cost in the range of $2.5-$3.0 million. A typical 345:138 kV phase shifting transformer can cost in the range of $6-$8 million. Therefore, transformers have a very good reason to have protective relay schemes on them, as you do not want to have to replace them often.

Problem Definition

Using the diagram in figure 1, we needed to construct a protective relaying scheme that could protect the transformer. We needed to design a scheme that would allow the transformer to stay in service when operating under normal conditions, but to trip out of service when any faults or other condition other than normal is reached.
Figure 1: Transformer and Circuit Breakers between 345 kV and 138 kV busses

Design Specifications

Transformer:

- 300/400/500 MVA @ 55°C
- 324/450/562.5 MVA @ 65°C
- 345:140:13.8 kV
- Load Tap Changing
- Wye: Wye: Delta winding configuration
- (3) high side CTs, multi ratio 2000:5, C800
- (3) high side CTs, multi ratio 3000:5 @ 2000:5, C800
- (6) medium side CTs, multi ratio 3000:5, C800
- (3) low side CTs, multi ratio 2000:5 C800

SEL-387 Relay:

- Current differential relay
- 4 input current differential protection
- 4 input overcurrent elements
- Wye or Delta connected
- 1 or 5 A secondary current
- Transformer capacity, 0.2-5,000 MVA
- Line-to-Line voltage, 1-1000 kV
- Second Harmonic Blocking capabilities

Assumptions:

- \( S_{base} \) for transformer calculations = 562.5 MVA
- \( V_{prefault} = 1 \angle 0^\circ \) p.u.
- Tertiary winding will not be used
DIFFERENTIAL ELEMENT SETTINGS

Table 3.1 shows the SEL-387 Relay settings, definitions, and setting ranges for the differential elements.

<table>
<thead>
<tr>
<th>Setting Label</th>
<th>Definition</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>RID</td>
<td>Relay Identifier</td>
<td>39 characters, (0 - 9, A - Z, -, /, , space)</td>
</tr>
<tr>
<td>TID</td>
<td>Terminal Identifier</td>
<td>59 characters, (0 - 9, A - Z, -, /, , space)</td>
</tr>
<tr>
<td>E87W1</td>
<td>Enable Winding 1 in Differential</td>
<td>Y, N</td>
</tr>
<tr>
<td>E87W2</td>
<td>Enable Winding 2 in Differential</td>
<td>Y, N</td>
</tr>
<tr>
<td>E87W3</td>
<td>Enable Winding 3 in Differential</td>
<td>Y, N</td>
</tr>
<tr>
<td>E87W4</td>
<td>Enable Winding 4 in Differential</td>
<td>Y, N</td>
</tr>
<tr>
<td>W1CT</td>
<td>Winding 1 CT Connection (delta, wye)</td>
<td>D, Y</td>
</tr>
<tr>
<td>W2CT</td>
<td>Winding 2 CT Connection (delta, wye)</td>
<td>D, Y</td>
</tr>
<tr>
<td>W3CT</td>
<td>Winding 3 CT Connection (delta, wye)</td>
<td>D, Y</td>
</tr>
<tr>
<td>W4CT</td>
<td>Winding 4 CT Connection (delta, wye)</td>
<td>D, Y</td>
</tr>
<tr>
<td>CTR1</td>
<td>Winding 1 CT Ratio (I_{PHi} / I_{HN})</td>
<td>1 - 50,000</td>
</tr>
<tr>
<td>CTR2</td>
<td>Winding 2 CT Ratio (I_{PHi} / I_{HN})</td>
<td>1 - 50,000</td>
</tr>
<tr>
<td>CTR3</td>
<td>Winding 3 CT Ratio (I_{PHi} / I_{HN})</td>
<td>1 - 50,000</td>
</tr>
<tr>
<td>CTR4</td>
<td>Winding 4 CT Ratio (I_{PHi} / I_{HN})</td>
<td>1 - 50,000</td>
</tr>
<tr>
<td>MVA</td>
<td>Maximum Transformer Capacity, Three-Phase MVA</td>
<td>OFF, 0.2 - 5,000 MVA</td>
</tr>
<tr>
<td>ICOM</td>
<td>Define Internal Winding / CT Connection Compensation</td>
<td>Y, N</td>
</tr>
<tr>
<td>W1CTC</td>
<td>Winding 1 Connection Compensation</td>
<td>0, 1, 11</td>
</tr>
<tr>
<td>W2CTC</td>
<td>Winding 2 Connection Compensation</td>
<td>0, 1, 11</td>
</tr>
<tr>
<td>W3CTC</td>
<td>Winding 3 Connection Compensation</td>
<td>0, 1, 11</td>
</tr>
<tr>
<td>W4CTC</td>
<td>Winding 4 Connection Compensation</td>
<td>0, 1, 11</td>
</tr>
<tr>
<td>VWDG1</td>
<td>Winding 1 Line-to-Line Voltage, kV</td>
<td>1 - 1000 kV</td>
</tr>
<tr>
<td>VWDG2</td>
<td>Winding 2 Line-to-Line Voltage, kV</td>
<td>1 - 1000 kV</td>
</tr>
<tr>
<td>VWDG3</td>
<td>Winding 3 Line-to-Line Voltage, kV</td>
<td>1 - 1000 kV</td>
</tr>
<tr>
<td>Setting Label</td>
<td>Definition</td>
<td>Limits</td>
</tr>
<tr>
<td>--------------</td>
<td>------------</td>
<td>--------</td>
</tr>
<tr>
<td>VWDG4</td>
<td>Winding 4 Line-to-Line Voltage, kV</td>
<td>1 - 1000 kV</td>
</tr>
</tbody>
</table>
| TAP1         | Winding 1 Current Tap (relay calculates based on MVA, etc.; user must define if MVA = OFF) | $(0.1 - 31) \cdot I_N$  
**Note:** $TAP_{\text{MAX}} / TAP_{\text{MIN}}$ must be less than or equal to 7.5 |
| TAP2         | Winding 2 Current Tap (as with TAP1) | $(0.1 - 31) \cdot I_N$ |
| TAP3         | Winding 3 Current Tap (as with TAP1) | $(0.1 - 31) \cdot I_N$ |
| TAP4         | Winding 4 Current Tap (as with TAP1) | $(0.1 - 31) \cdot I_N$ |
| O87P         | Restrained Element Operating Current Minimum Pickup, per unit of TAP | $(0.1 - 1.0) \cdot TAP$  
**Note:** $TAP_{\text{MIN}} \cdot O87P \geq 0.1 \cdot I_N$ |
| SLP1         | Restrained Element Slope 1, percent | 5 - 100% |
| SLP2         | Restrained Element Slope 2, percent | OFF, 25 - 200% |
| IRS1         | Restrained Element Slope 1 Limit; intersection of SLP1 and SLP2. (only used if SLP2 is not OFF) | $(1.0 - 20.0) \cdot TAP$  
**Note:** $TAP_{\text{MAX}} \cdot IRS1 \leq 31.0 \cdot I_N$ |
| U87P         | Unrestrained Element Operating Current Pickup Level | $(1.0 - 20.0) \cdot TAP$  
**Note:** $TAP_{\text{MAX}} \cdot U87P \leq 31.0 \cdot I_N$ |
| PCT2         | Second-Harmonic Blocking Percentage of Fundamental | OFF, 5 - 100% |
| PCT5         | Fifth-Harmonic Blocking Percentage of Fundamental | OFF, 5 - 100% |
| TH5P         | Fifth-Harmonic Alarm Threshold | OFF, $(0.02 - 3.2) \cdot TAP$  
**Note:** $TAP_{\text{MIN}} \cdot TH5P \geq 0.05 \cdot I_N$  
**Note:** $TAP_{\text{MAX}} \cdot TH5P \leq 31.0 \cdot I_N$ |
| TH5D         | Fifth-Harmonic Alarm Time Delay Pickup | 0 - 8000 cycles |
| IHBL         | Independent Harmonic Blocking (block only the restrained 87 element seeing excessive second or fifth harmonic) | $Y, N$  
$(N = \text{any harmonic blocking element blocks all 87R elements})$ |
Configuring the SEL-387

Procedure

The first step in configuring the SEL-387 is to decide which CTs to connect to the relay and what positions they need to connect to. We decided that we would connect the high side transformer CTs to winding 1 on the relay, and to connect the low side transformer CTs to winding 2 of the relay. The next step is to input the CT ratios that are used in the connection to the relay. With this accomplished, we can then input the maximum MVA rating of the transformer, which is 562.5 MVA.

The next step was actually quite unique. Normally, the CTs connected to a Wye configured transformer, would be connected in a delta configuration, this is to keep the phase shift of the currents equal, but with the SEL-387, the CTs can easily be connected in any configuration. This is done through an internal compensation that the microprocessor of the relay calculates with the aid of an assigned compensation matrix. This assignment is made when configuring the relay. Because we are trying to learn the most we can about the relay, we decided that we would connect the CTs in a Wye configuration, as the transformer is also connected in Wye.

The next step is to enter the voltages that are connected to the windings of the relay. The ensuing step is actually done by the relay, but we can do it manually to show what is done by the relay to configure itself to protect the transformer. This internal calculation is the tap current setting. The equation that is used is as follows:

\[ TAP_n = \frac{MVA \cdot 1000}{\sqrt{3} \cdot VWDGn \cdot CTRn} \cdot C \quad (C = 1 \text{ for wye CTs}) \]

These calculations can be found in the appendix, along with all of the settings that we used for our relay.

The last settings that need to be made deal with the harmonic blocking, current restraints, and current pickup. The harmonic blocking settings of the relay play an integral part of the protection of the transformer. The relay needs to be blocked from operation when the transformer is first energized, and when it is overexcited.

When the transformer is initially energized, it produces a large amount of inrush current. This inrush current can be seen to the relay as fault current, and therefore making it trip, but when in fact it is just the transformer energizing. Since this inrush current is primarily made of the Second Harmonic, we can block operation of the relay by blocking out the Second Harmonic. Since inrush current is normally higher than 30% of normal current, we decided to set the relay to block the Second Harmonic for anything above 15%.
When the transformer gets over-excited, it produces a large amount of current. This current is mainly composed of the Fifth Harmonic. Therefore if we block operation of the relay for large amounts of fault current due to the Fifth Harmonic, we can make sure the relay stays in use for the entire duration that it is needed. Since the currents during overexcitation are usually larger than 35% of the normal current, we set the relay to not trip for anything over 35%. This allows it to trip for everything but overexcitation.

Current restraints and pickups are for indicating the difference between an internal and external fault, and for tripping due to an internal fault, respectively. The current restraint allows for the currents to be a little higher than normal and not trip. This allows the relay to see if the situation persists, and to see if the fault is internal to the transformer or not, then to see if it needs to act. The current pickup is set to about 10 times the normal current magnitude. This allows for the relay to trip out very fast when it realizes that a fault is internal.

Summary

Once we decided on all of the settings that we were going to use, we then needed to calculate the actual numbers that we were going to enter into the relay. These settings can be seen in the appendix. Along with setting the relay, we realized that the current differential relay was only part of the protection scheme. Along with the differential relay, we need a; high temperature relay, a low oil level relay, a sudden pressure change relay, and a lock out relay for all these relays to feed into. A diagram of a full protection scheme can be seen in figure 2.

![Figure 2. Full protection scheme for project transformer](image)

Conclusions

Even though we were not able to test our relay’s settings, we believe that the settings are correct. This is due to the fact that after careful deliberation and reading the relay manual and the transformer specification sheet many times, we feel that the relay would perform as needed. We cannot find any reason that the relay would not perform as expected. The
calculations that were used are correct and the theory behind the relay seems to be correct also.

The settings could easily be tested if the SEL-387 was available to be tested. If someday a relay is donated to the school, one could look at these settings and see if they would work for a two winding transformer.

System Application?
- What is xformer impedance?
- Thru Faults?
- CT saturation?
APPENDIX A
# CONFIGURATION SETTINGS

- **Relay Identifier (39 Characters)**
  - RID = Bottle Creek Z

- **Terminal Identifier (59 Characters)**
  - TID =

<table>
<thead>
<tr>
<th>Setting</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enable Winding 1 in Differential Element (Y, N)</td>
<td>E87W1</td>
</tr>
<tr>
<td>Enable Winding 2 in Differential Element (Y, N)</td>
<td>E87W2</td>
</tr>
<tr>
<td>Enable Winding 3 in Differential Element (Y, N)</td>
<td>E87W3</td>
</tr>
<tr>
<td>Enable Winding 4 in Differential Element (Y, N)</td>
<td>E87W4</td>
</tr>
<tr>
<td>Enable Winding 1 O/C Elements and Dmd Thresholds (Y, N)</td>
<td>EOC1</td>
</tr>
<tr>
<td>Enable Winding 2 O/C Elements and Dmd Thresholds (Y, N)</td>
<td>EOC2</td>
</tr>
<tr>
<td>Enable Winding 3 O/C Elements and Dmd Thresholds (Y, N)</td>
<td>EOC3</td>
</tr>
<tr>
<td>Enable Winding 4 O/C Elements and Dmd Thresholds (Y, N)</td>
<td>EOC4</td>
</tr>
<tr>
<td>Enable Combined O/C Elements (Y, N)</td>
<td>EOCc</td>
</tr>
<tr>
<td>Enable SELOGIC® Control Equations Set 1 (Y, N)</td>
<td>ESLS1</td>
</tr>
<tr>
<td>Enable SELOGIC® Control Equations Set 2 (Y, N)</td>
<td>ESLS2</td>
</tr>
<tr>
<td>Enable SELOGIC® Control Equations Set 3 (Y, N)</td>
<td>ESLS3</td>
</tr>
</tbody>
</table>

# GENERAL DATA

<table>
<thead>
<tr>
<th>Setting</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winding 1 CT Connection (D, Y)</td>
<td>W1CT</td>
</tr>
<tr>
<td>Winding 2 CT Connection (D, Y)</td>
<td>W2CT</td>
</tr>
<tr>
<td>Winding 3 CT Connection (D, Y)</td>
<td>W3CT</td>
</tr>
<tr>
<td>Winding 4 CT Connection (D, Y)</td>
<td>W4CT</td>
</tr>
<tr>
<td>Winding 1 CT Ratio (1 - 50000)</td>
<td>CTR1</td>
</tr>
<tr>
<td>Winding 2 CT Ratio (1 - 50000)</td>
<td>CTR2</td>
</tr>
<tr>
<td>Winding 3 CT Ratio (1 - 50000)</td>
<td>CTR3</td>
</tr>
<tr>
<td>Winding 4 CT Ratio (1 - 50000)</td>
<td>CTR4</td>
</tr>
<tr>
<td>Maximum Power Transformer Capacity (OFF, 0.2 - 5000 MVA)</td>
<td>MVA</td>
</tr>
<tr>
<td>Define Internal CT Connection Compensation (Y, N)</td>
<td>ICOM</td>
</tr>
<tr>
<td>Winding 1 CT Conn. Compensation (0, 1, ..., 12)</td>
<td>W1CTC</td>
</tr>
<tr>
<td>Winding 2 CT Conn. Compensation (0, 1, ..., 12)</td>
<td>W2CTC</td>
</tr>
<tr>
<td>Winding 3 CT Conn. Compensation (0, 1, ..., 12)</td>
<td>W3CTC</td>
</tr>
<tr>
<td>Winding 4 CT Conn. Compensation (0, 1, ..., 12)</td>
<td>W4CTC</td>
</tr>
<tr>
<td>Winding 1 Line-to-Line Voltage (1 - 1000 kV)</td>
<td>VWDG1</td>
</tr>
<tr>
<td>Winding 2 Line-to-Line Voltage (1 - 1000 kV)</td>
<td>VWDG2</td>
</tr>
<tr>
<td>Winding 3 Line-to-Line Voltage (1 - 1000 kV)</td>
<td>VWDG3</td>
</tr>
<tr>
<td>Winding 4 Line-to-Line Voltage (1 - 1000 kV)</td>
<td>VWDG4</td>
</tr>
</tbody>
</table>
### Differential Elements

(Note: TAP1 - TAP4 are auto-set by relay if MVA setting is not OFF.)

<table>
<thead>
<tr>
<th>Element Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winding 1 Current Tap (0.5 - 155 A secondary)</td>
<td>TAP1</td>
</tr>
<tr>
<td>Winding 2 Current Tap (0.5 - 155 A secondary)</td>
<td>TAP2</td>
</tr>
<tr>
<td>Winding 3 Current Tap (0.5 - 155 A secondary)</td>
<td>TAP3</td>
</tr>
<tr>
<td>Winding 4 Current Tap (0.5 - 155 A secondary)</td>
<td>TAP4</td>
</tr>
<tr>
<td>Restrained Element Operating Current PU ((0.1-1.0) multiple of TAP)</td>
<td>O87P</td>
</tr>
<tr>
<td>Restriction Slope 1 Percentage (5 - 100%)</td>
<td>SLP1</td>
</tr>
<tr>
<td>Restriction Slope 2 Percentage (25 - 200%)</td>
<td>SLP2</td>
</tr>
<tr>
<td>Restriction Current Slope Limit (1.2 - 20) multiple of TAP</td>
<td>IRS1</td>
</tr>
<tr>
<td>Unrestrained Element Current PU ((1 - 20) multiple of TAP)</td>
<td>U87P</td>
</tr>
<tr>
<td>Second-Harmonic Blocking Percentage (OFF, 5 - 100%)</td>
<td>PCT2</td>
</tr>
<tr>
<td>Fifth-Harmonic Blocking Percentage (OFF, 5 - 100%)</td>
<td>PCT5</td>
</tr>
<tr>
<td>Fifth-Harmonic Alarm Threshold (OFF, 0.02 - 3.2) multiple of TAP</td>
<td>TH5P</td>
</tr>
<tr>
<td>Fifth-Harmonic Alarm TDPU (0 - 8000 cycles)</td>
<td>TH5D</td>
</tr>
<tr>
<td>Independent Harmonic Blocking (Y, N)</td>
<td>IHBL</td>
</tr>
</tbody>
</table>

### Restricted Earth Fault

- Enable 321 (SELogic Control Equations)
  - E321 =
- Operating Quantity from Wdg. 1, Wdg. 2, Wdg. 3 (1, 2, 3, 12, 123)
  - 321OP =
- Positive-Sequence Current Restraint Factor, 10/11 (0.02 - 0.50)
  - a0 =
- Residual Current Sensitivity Threshold (0.25 - 15.00 A)
  - 50GP =

### Winding 1 O/C Elements

- Phase Def.-Time O/C Level 1 PU (OFF, 0.25 - 100 A secondary)
  - 50P11P =
- Phase Level 1 O/C Delay (0 - 6000 cycles)
  - 50P11D =
- 50P11 Torque Control (SELogic Control Equations)
  - 50P11TC =
- Phase Inst. O/C Level 2 PU (OFF, 0.25 - 100 A secondary)
  - 50P12P =
- 50P12 Torque Control (SELogic Control Equations)
  - 50P12TC =
- Phase Inst. O/C Level 3 PU (OFF, 0.25 - 100 A secondary)
  - 50P13P =
- Phase Inst. O/C Level 4 PU (OFF, 0.25 - 100 A secondary)
  - 50P14P =
- Phase Inv.-Time O/C PU (OFF, 0.5 - 16 A secondary)
  - 51P1P =
- Phase Inv.-Time O/C Curve (U1 - U5, C1 - C5)
  - 51P1C =
- Phase Inv.-Time O/C Time-Dial (US 0.5 - 15, IEC 0.05 - 1)
  - 51P1TD =
- Phase Inv.-Time O/C EM Reset (Y, N)
  - 51PDRS =
- 51P1 Torque Control (SELogic Control Equations)
  - 51P1TC =
APPENDIX B
\( MVA = \text{Max Power Capacity of Transformer (MVA)} \)
\( V\text{WDG} = \text{Voltage level at Line-to-Line Winding connection (kV)} \)
\( CTR = \text{Current Transformer Ratio} \)

\[
T_{ap1} = \frac{MVA \cdot 1000}{\sqrt{3} \cdot V\text{WDG1} \cdot CTR1}
\
= \frac{562.5 \; \text{MVA} \cdot 1000}{\sqrt{3} \cdot 345 \; \text{kV} \cdot (\frac{2000}{5})}
\
T_{ap1} = 2.35 \quad \text{use highest possible taps, usually.}
\]

\[
T_{ap2} = \frac{MVA \cdot 1000}{\sqrt{3} \cdot V\text{WDG2} \cdot CTR2}
\
= \frac{562.5 \; \text{MVA} \cdot 1000}{\sqrt{3} \cdot 138 \; \text{kV} \cdot (\frac{3000}{5})}
\
= 3.92
\]

Error check

\[
\frac{T_{ap2}}{T_{ap1}} \leq 7.5
\
\frac{3.92}{2.35} = 1.66 \leq 7.5 \Rightarrow \text{OK}
\]
Error check for current pickup

\[ 0.87p > \frac{(1 \cdot I_n)}{\text{MinTop}} \]

\[ 0.87p > \frac{(0.1 \cdot 5)}{2.35} \]

\[ 0.87p > \frac{4.5}{2.35} \]

\[ 0.87p > 1.928 \]

\[ 0.87p = 0.3 \]

\[ \text{explain!} \]