Event Analysis Report

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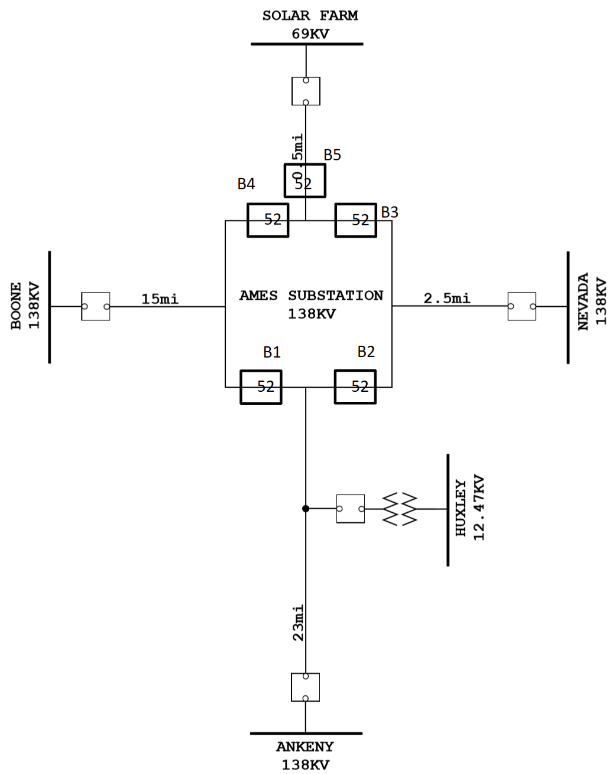
Overview



The PSCAD is a critical tool for the simulation and dynamic analysis of the Ames Substation project, particularly for the following aspects:

1. **Dynamic simulations**

- **Fault Condition**: PSCAD is used to simulate and test various fault conditions on transmission lines (with different faults such as line to ground fault, line to line, single line to ground, and three phase fault).
- **Relay Responses**: Testing how relays such as SEL-411L, SEL-421, and SEL-487E detect and clear faults without causing unnecessary breaker trips or cascading failures.

2. **Protection Scheme Testing**

- **Line Protection:**

    - Simulations validate the chosen protection schemes like Directional comparison Blocking (BCB), Permissive Overreaching Transfer Trip (POTT), and Line Current Differential (87L)
    - Relay's coordination and timing are tested to ensure proper isolation of faulted sections.
- **Transformer Protection**: Transformer differential protection (87T) implemented with SEL-487E is tested for accuracy in detecting internal faults versus external events like inrush currents. (instantaneous high input current drawn by the a power supply when first turn-on)

3. Communication Systems

- PSCAD models the communication media, such as Power Line Carrier (PLC) for Ames to Ankeny and Optical Ground Wire (OGW) for the rest of the lines.
- Simulations include delays, noise, and signal integrity to ensure robust relay communication under real-world conditions.

4. Event Analysis

- **Pre-Faults and Post-Fault States**: PSCAD logs data before, during, and after fault events to analyze breaker operation, relay logic, and system stability.
- **Breaker Operations**: Simulations ensure that all breakers (such as B1 to B5, Solar Farm breaker, Nevada breaker, Boone breaker, and Ankeny breaker) operate within defined parameters, including clearing times and trips-coil (a component in a circuit breaker that used to interrupt fault current and voltages to protect downstream systems) responses.

5. Integration Testing

- **Pilot Schemes**: Integration of pilot schemes like DCB and 87L with system components (relays, breakers, and communication channels) is verified in PSCAD.
- **I/O Assignment**s: Input/Output configurations for relays are modeled to ensure proper relay operation during simulated faults.

❖ **Key Testing Scenarios in PSCAD**

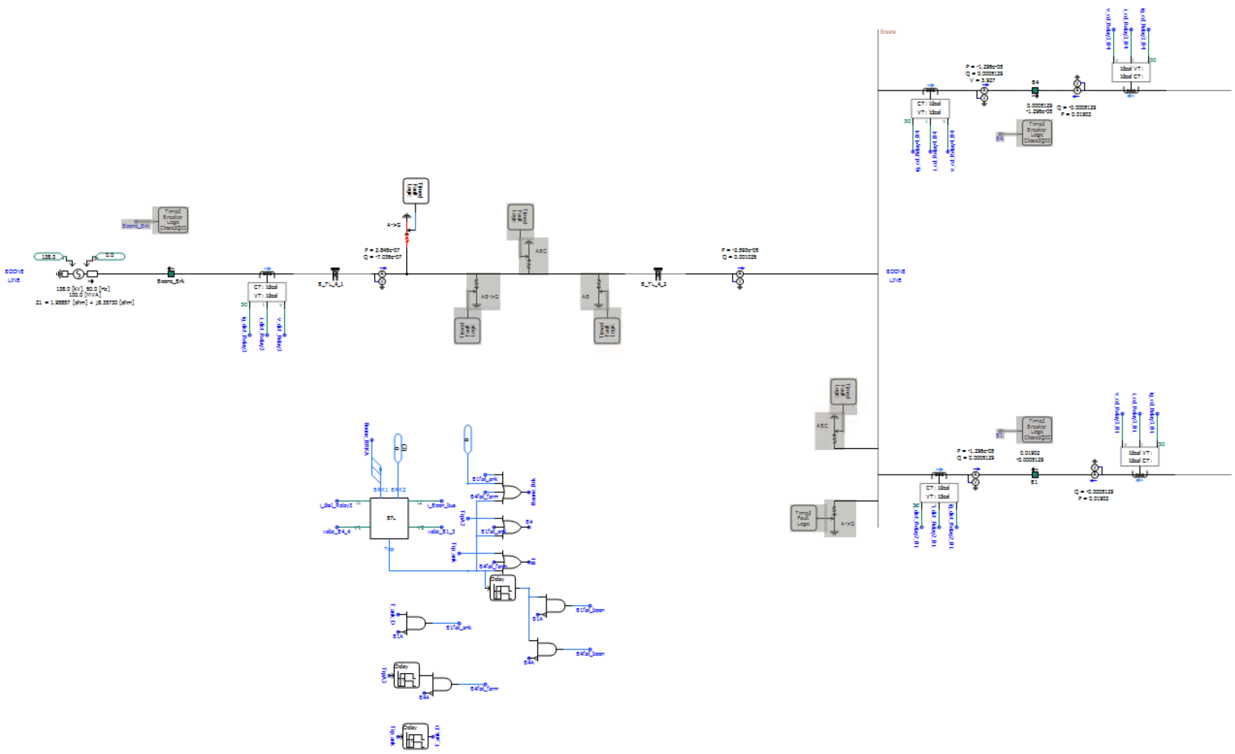
- ➢ Transmission Line Faults
  - ■ Simulating faults on Ames to Ankeny line, Ames to Boone line, Ames to Nevada line, and Ames to Solar Farm.
  - ■ Observing fault-clearing times and verifying relay coordination.
- ➢ Breaker Failures
  - ■ Introducing breaker failure conditions to test backup relaying such as SEL-352 and Direct Transfer Trip (DTT) signals.
- ➢ Transformer Protection
  - ■ Simulating internal and external faults for the 10 MVA step-up auto-transformer to validate differential protection logic.
- ➢ Arc Flash and Line to Line Faults
  - ■ Testing the system's resilience and fault isolation capabilities.

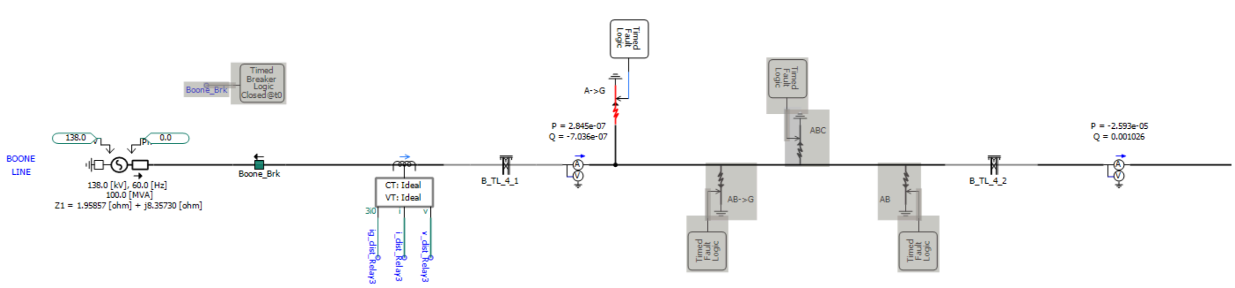
❖ **Visualization and Reporting**

- ➢ Single-Line Diagrams: PSCAD provides a visual representation of the substation, showing how relays and breakers interact during simulated events.
- ➢ Event Logs: Detailed logs are generated to analyze system behavior and verify compliance with IEEE standards (e.g., C37.91-2021 for transformer protection, C37.113-2015 for transmission line protection).

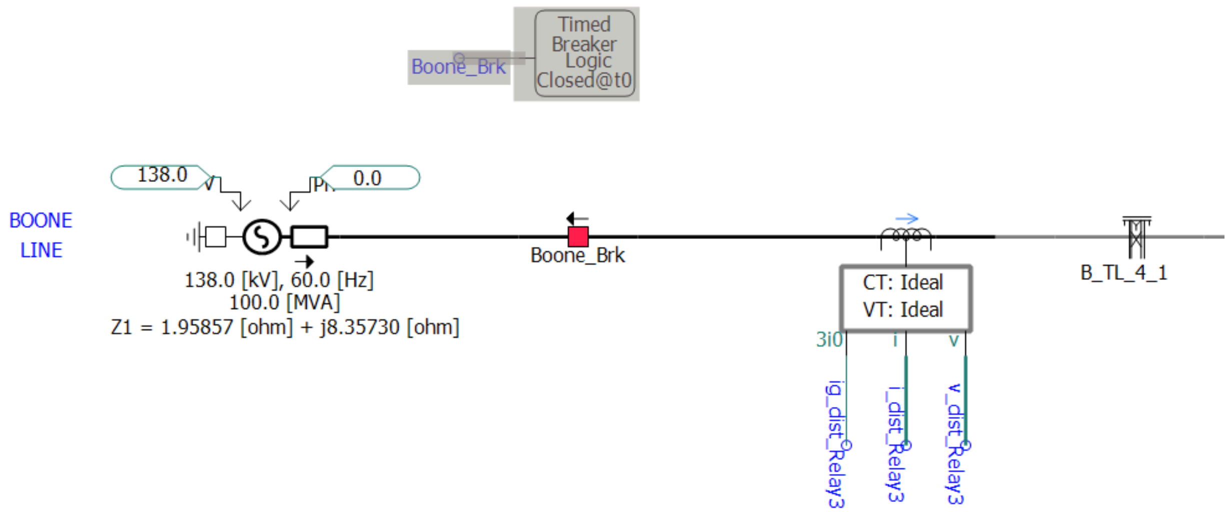
Boone Line Faults

Boone Line Big picture

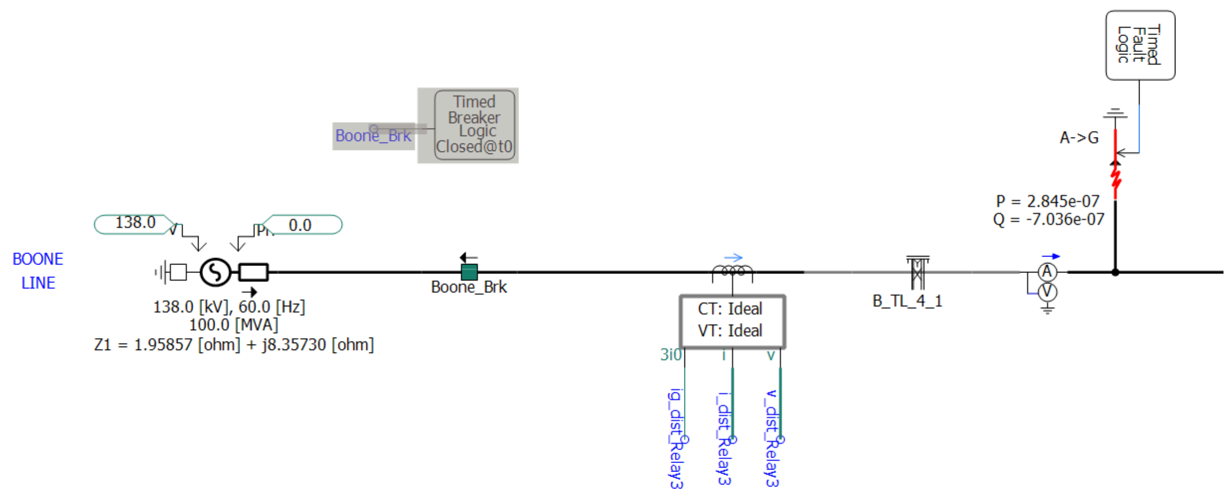




Breakers That Successfully Operated During Fault:



The breaker is red indicating the breaker is closed



The breaker is green indicating the breaker is open.

A. Boone_Brk

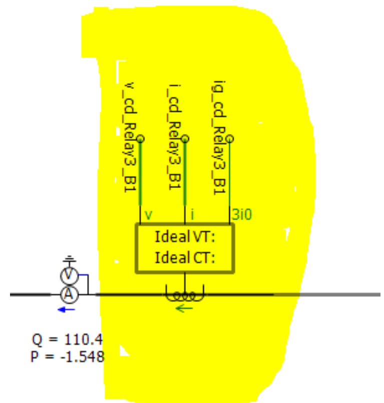
a. Operation:

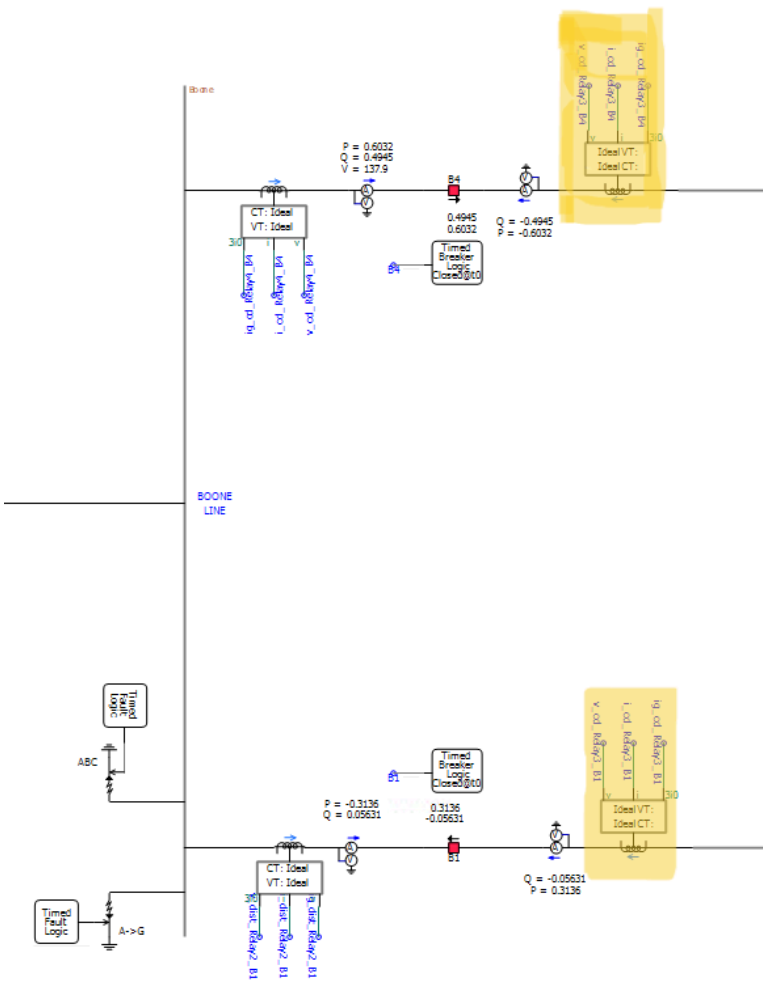
- ➢ Boone_Brk trips if there is a fault on the boone line cutting power from the remote substation. If the current differential relay measured the feed current from boone does not match the measured feed from the Ames substation the breaker trips.

B. B4 & B1

a. Operation:

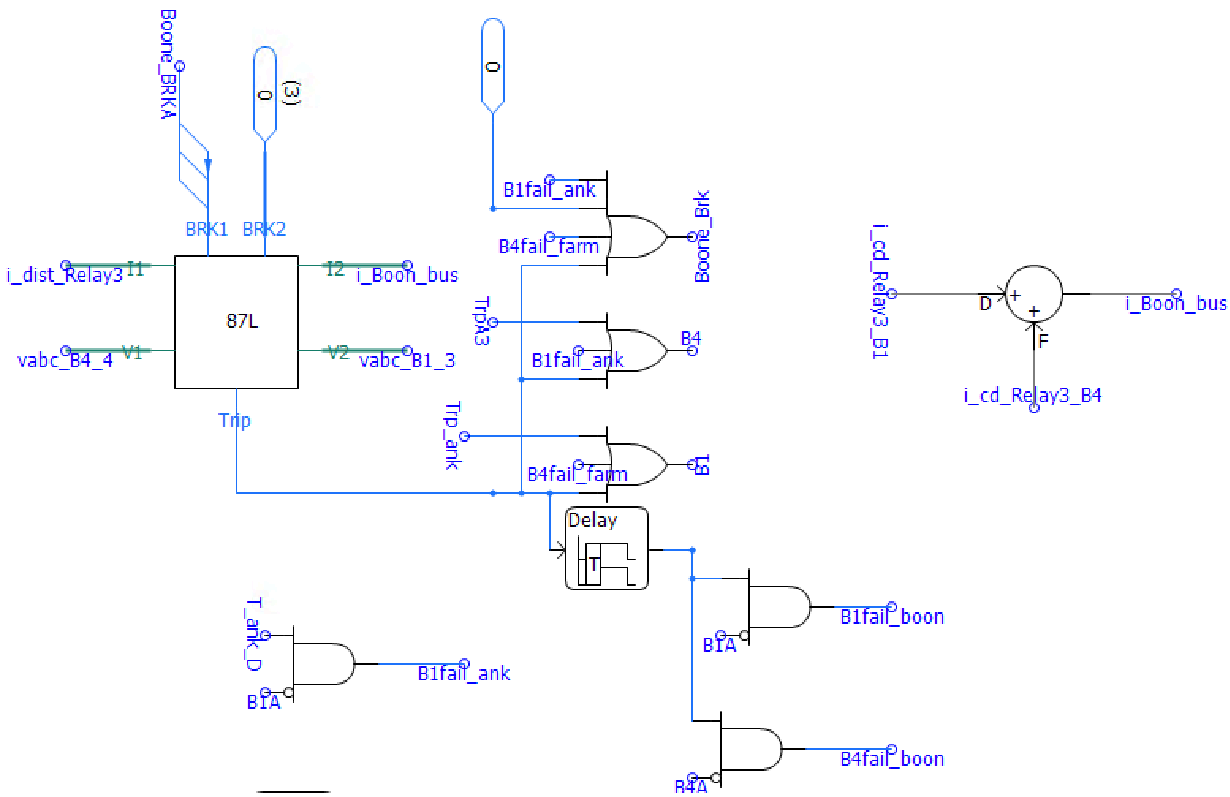
- ➢ B4 & B1 trip for the boone line due to the ring bus configuration. To fully isolate the line we see the current differential relay is set to trip both breakers.
- ➢ To ensure all of the current entering the line is correctly measured the orientation of the CTs is crucial. Notice both CTs are pointed in to the line and are on the outside of the breaker to ensure the protection zones of the relays overlap


v_cd_Relay3_B1
i_cd_Relay3_B1
ig_cd_Relay3_B1
v
i
3i0
Ideal VT:
Ideal CT:
Q = 110.4
P = -1.548

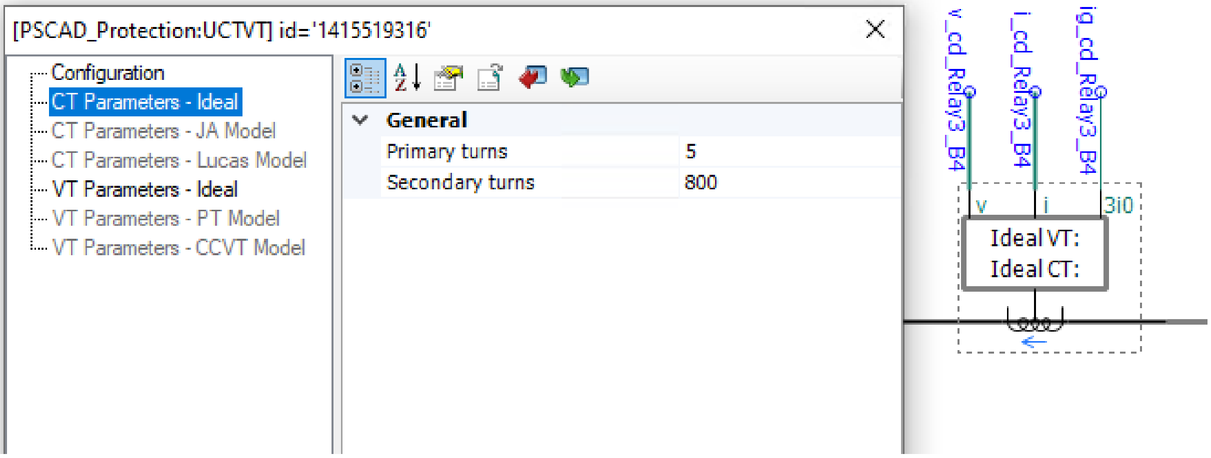

BOONE
LINE
P = 0.6032
Q = 0.4945
V = 137.9
B4
0.4945
0.6032
Q = -0.4945
P = -0.6032
CT: Ideal
VT: Ideal
Timed
Breaker
Logic
Ideal VT:
Ideal CT:
Timed
Fault
Logic
ABC
A->G
P = -0.3136
Q = 0.05631
0.3136
-0.05631
B1
Q = -0.05631
P = 0.3136
v_cd_Relay3_B1
i_cd_Relay3_B1
ig_cd_Relay3_B1

❖ **Steps in Fault Isolation**

➢ **Fault Detection:** The relay at Boone_Brk detects the fault on the Boone line by observing the current does not match the measured current on the Ames end of the line. The 87L relay sends trip signals to the 3 breakers. In practice these signals are sent through an optical ground wire with one relay on each end of the line that coordinate with each other. To simplify the circuit in PSCAD one 87L relay is used with trip signals sent to each breaker from one trip signal. Notice in the image of the relay that the currents from the CTs measured at the bus are added together using the sum block. All CT parameters are set to model them as ideal with a 800:5 current ratio.



➢ It is important to note that the CT ratios must be the same for the 87L scheme to function correctly. One error made was not checking all of the CTs were configured correctly which led to over tripping of the circuit.



Current and Voltage Fault Behavior (1PH A-G at 50% of Line Length)

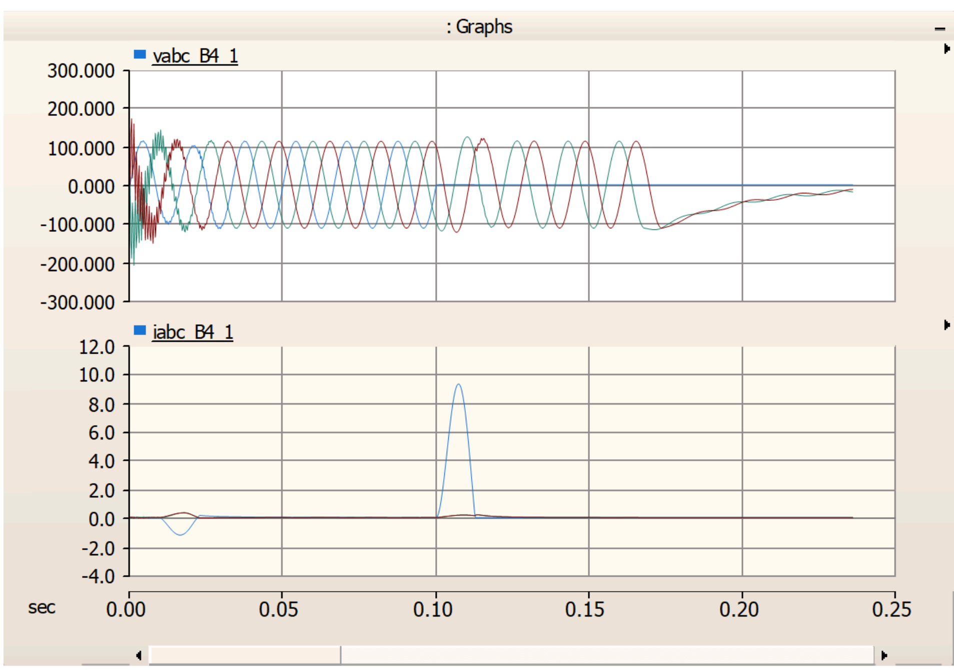
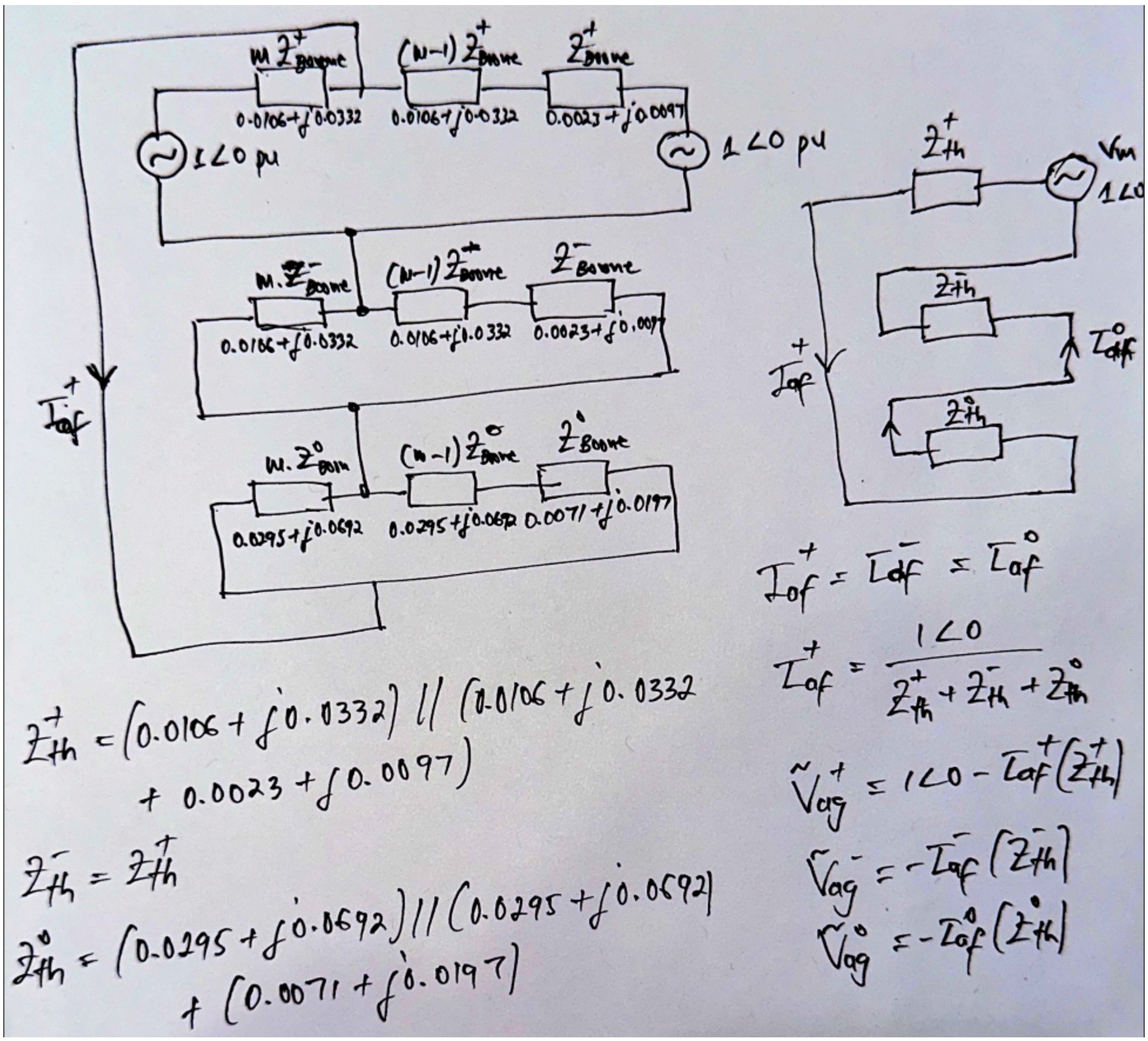


Figure shows the Voltage (top graph) and Current (bottom graph) waveforms during the fault at .1 seconds single line to ground 50% Boone Line.

Circuit Verification:

If you develop a model for this circuit ignoring the solar farm line, and looking at the Ankeny Line and Nevada Line as Thevinin equivalent circuits the sequence model can be represented as shown.



Using the formulas provided in the above figure the following calculations can be made to identify the fault current and voltage.

```
Vb = 138000;
P3b = 100000000;
Zbase = (Vb/sqrt(3))^2/P3b;
Ib = P3b/(Vb/sqrt(3));


% Ankeny SEQUENCE IMPEDANCE MATRIX (Zsq) [ohms/m]:
ZsAnk = [(0.374440633E-03 + 0.103468759E-02j) 0 0;0 (0.118952109E-03 + 0.510181584E-03j) 0;...
        0 0 (0.118952109E-03 + 0.510181584E-03j)];
ZsAnktotpu = 23*1609.34*ZsAnk/Zbase;

% Nevada SEQUENCE IMPEDANCE MATRIX (Zsq) [ohms/m]:
ZsNev = [(0.374506496E-03 + 0.103473304E-02j) 0 0; 0 (0.118952157E-03 + 0.510182077E-03j) 0;...
        0 0 (0.118952157E-03 + 0.510182077E-03j)];
ZsNevtotpu = 2.5*1609.34*ZsNev/Zbase;

% Boone Line SEQUENCE IMPEDANCE MATRIX (Zsq) [ohms/m]:
ZsB = [(0.465448305E-03 + 0.109166399E-02j) 0 0; 0 (0.167461073E-03 + 0.523772912E-03j) 0;...
      0 0 (0.167461073E-03 + 0.523772912E-03j)];
ZsBtotpu = 15*1609.34*ZsB./Zbase;

Zth = (ZsAnktotpu .* ZsNevtotpu)./(ZsNevtotpu + ZsAnktotpu);
```

```
%%
a = .0106+.0332j;
b = .0023+.0097j;
c = .0295+.0692j;
d = .0071+.0197j;
Zpos = a*(a+b)/(2*a+b);
Zneg = Zpos;
Zzero = c*(c+d)/(2*c+d);
If = 1/(Zpos + Zneg + Zzero);
Vagpos = 1-If*Zpos;
Vagneg = -1*If*(Zneg);
Vagzero = -1*If*(Zzero);
a = exp(2j*pi/3);
asq = exp(-2j*pi/3);
A = [1 1 1; asq a 1; a asq 1];



Vseq = [Vagpos;Vagneg;Vagzero];
Iseq = [If;If;If];
Iabc = A*Iseq;
Vabc = A*Vseq;
VABC = Vb*abs(Vabc)
IABC = Ib*abs(Iabc)
```

Figure shows MATLAB code for calculating the phase current and voltages during fault

VABC =

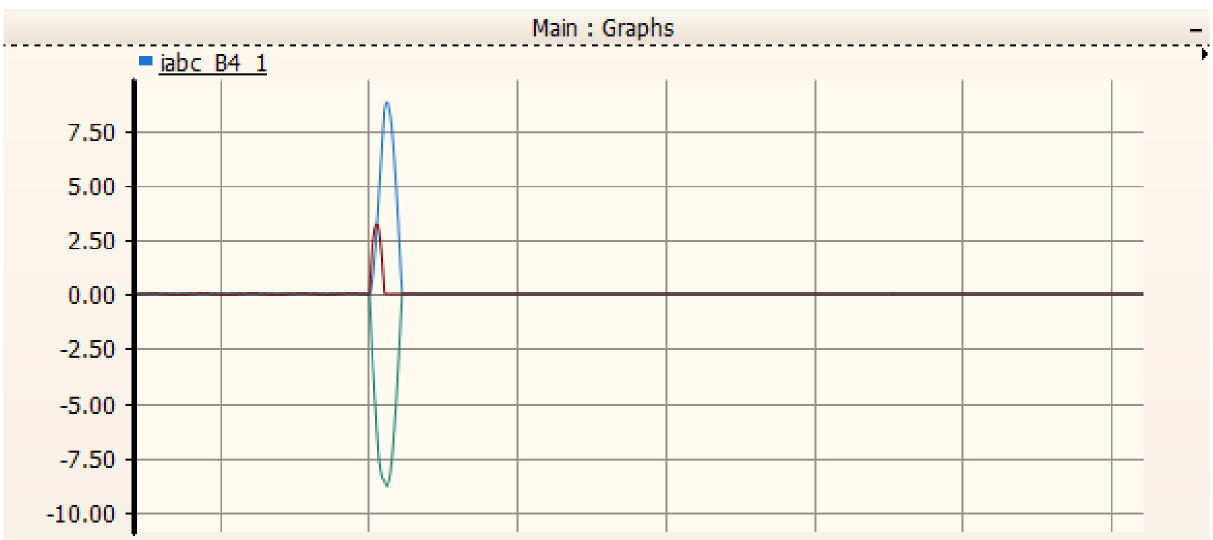
Va = 0.0000
Vb = 1.0e+05 *1.5697/sqrt(3)*sqrt(2) = 1.0e+05 *1.28
Vc = 1.0e+05 *1.6435/sqrt(3)*sqrt(2) = 1.0e+05 *1.34

IABC =

Ia = 1.0e+04 *4.6305 * sqrt(2) = 1.0e+04 *6.54
Ib = 0.0000
Ic = 0.0000

Note that these are provided as rms values to get the peak multiply by sqrt(2. This provides close approximation to the provided plots from PSCAD. Though these results are not as accurate as we would like they do a good job of matching what happens in each phase. The current level seen by the faulted phase peaks at about 9.2 and is zero for the other phases. The voltage peaks about 120 for the no fault phases and zero for the faulted phase.

Current Fault Behavior (3PH Fault ABC at 50% of Line Length)



A. Current Before Fault

a. Observation:

- ➢ Before the fault occurs, the current waveform is steady and sinusoidal across all three phases (named as phase A, B, and C).
- ➢ If you sum the currents the magnitude of the current is relatively low or constant, indicating normal operating conditions with balanced load flow through the system.

b. Reasoning

- ➢ This state represents the pre-fault condition where the system operates as designed
- ➢ There are no disturbances or abnormalities, and the load is evenly distributed across the phases.

B. Current During Fault

a. Observation:

- ➢ When the fault occurs, there is a sharp and sudden spike in current magnitude on one or more phases.
- ➢ The waveform becomes distorted, with a much higher magnitude than the pre-fault current. In some cases, only one or two phases show spikes, depending on the types of fault.

b. Reasoning:

- ➢ The fault introduces a low-impedance path for the current, leading to a significant rise in fault current. As for the behavior of the three phase fault, all three phases experienced high fault current.
- ➢ The differential relay (SEL-87L) detects the fault based on this abnormal current using Kirchhoff's Current Law to detect current flowing through the wrong path and sends a trip signal to the breakers (Boone_Brk, B1, and B4).

C. Current After Fault

a. Observation

- ➢ After the breakers (Boone_Brk, B1, and B4) trips, the current waveform in all phases drops to the initial point mean to zero.
- ➢ This indicates successful isolation of the faulted section by the protection system.

b. Reasoning

- ➢ The breakers open the circuit, preventing the flow of current to the faulted section.
- ➢ This action protects the system component such as transformer, transmission lines, and other equipment from damage due to sustained fault current.

Relays that operated for Boone Line Fault

1. **Primary Relay: SEL-411L**

   ➢ The SEL-411L relay provides 87L (Line Current Differential) for the Boone line

   ➢ The 87L protection detects faults by comparing the current entering and exiting the Boone line. If there is a mismatch, it indicates a fault within the line and triggers the relay.

   ➢ Our simplified model does not simulate a reclosing function that would normally be available, instead the circuit checks the breakers position if they are open the trip signal is locked in the trip position. If this was not used then the trip signal would bounce between open and closed as it only outputs a one (1) if the currents don't match on each end of the line. This means when the breakers clear the fault both ends of the line will have zero current and the 87L trip signal will go away. Instead OR logic gates are used to keep the 87L closed through tracking the breaker position.

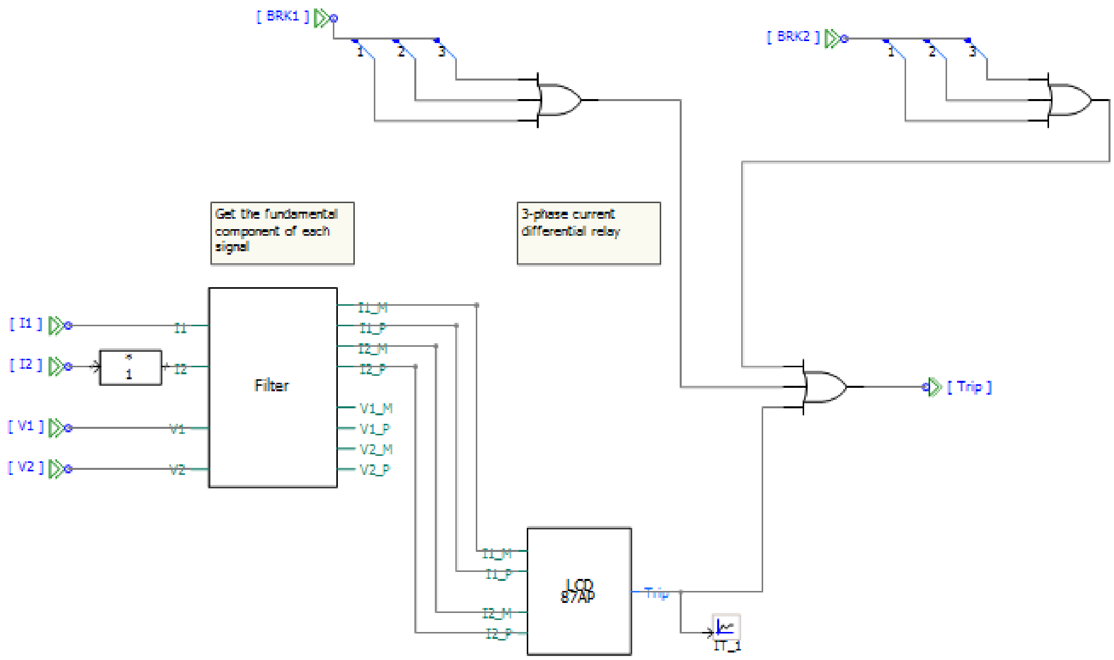


Figure shows the or gates used for the 87L relay used to hold the trip signal high when a fault occurs.

Role of 87L in the Coordination

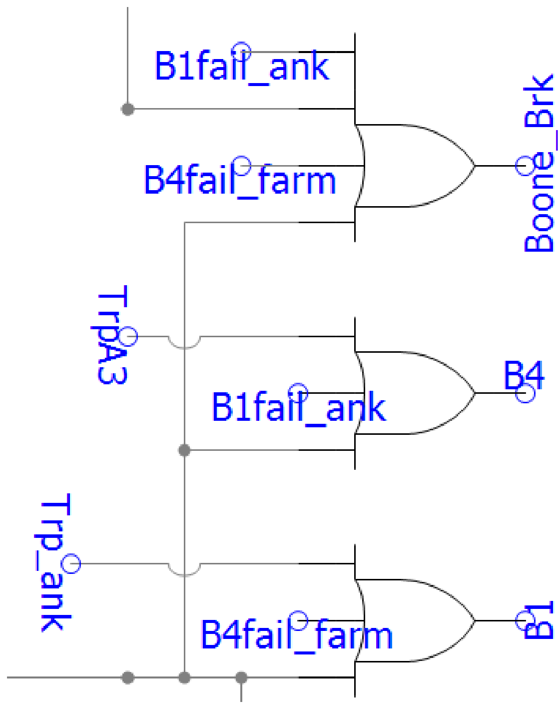
The 87L (Line Current Differential Protection) scheme is the primary protection mechanism for the Boone line.

How It Works:

➢ The 87L protection compares the currents measured at both ends of the line (e.g., at the Boone_Brk and the substation relay). If the currents do not match (indicating a fault within the Boone line), the relay at Boone_Brk trips immediately.

Communication:

➢ The 87L scheme relies on high-speed communication (via Optical Ground Wire) to exchange current data between relays on opposite ends of the line. This ensures fast and accurate fault detection and isolation. One thing to note is for each breaker multiple trip signals may be parallel together in practice, in PSCAD the signals will receive a source condition based on the logic of the simulation. To work around this each trip signal is ORed together shown below.

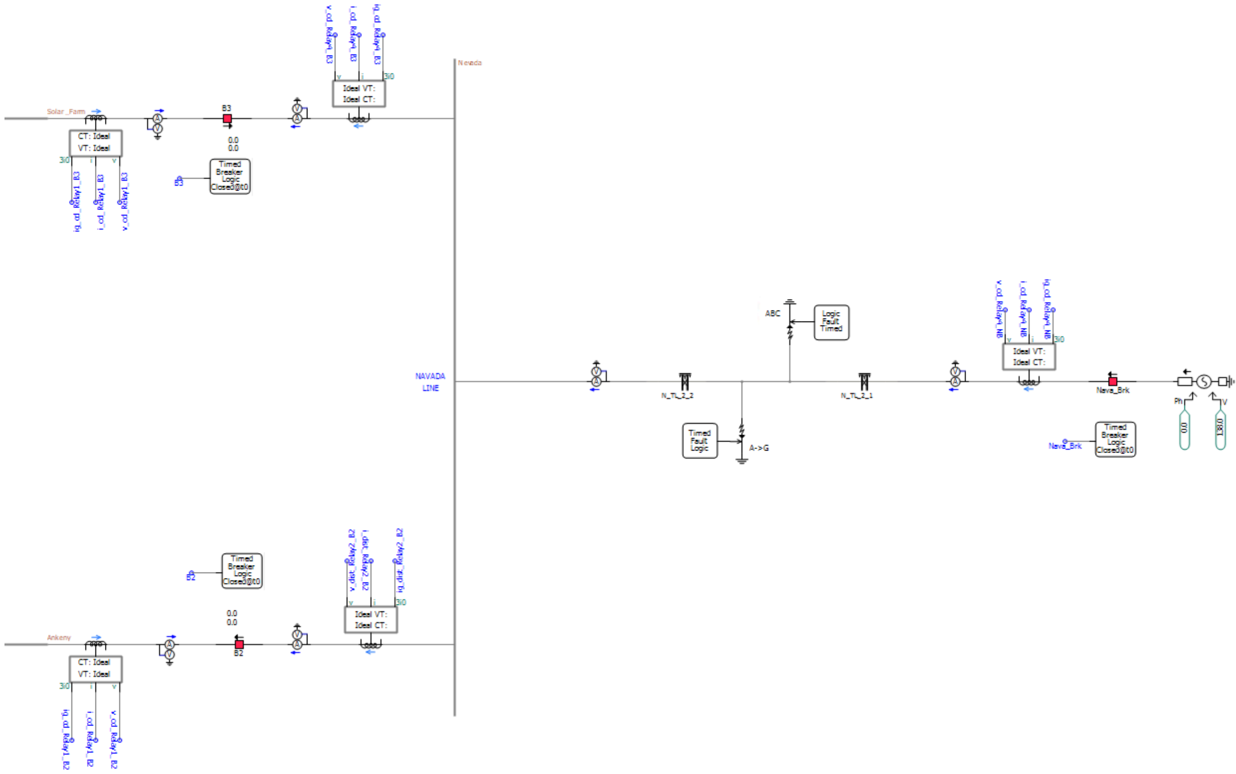


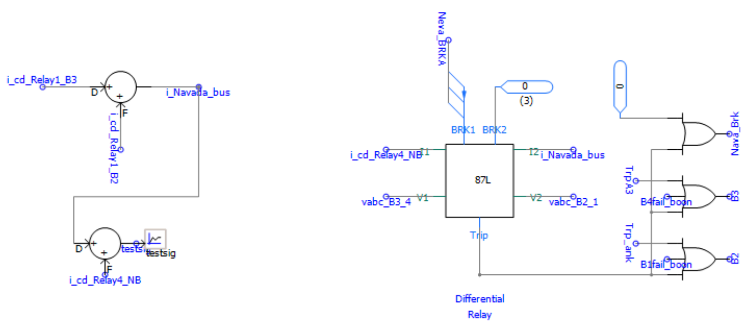
The figure shows Boone_Brk, B4, & B1 signals which control the position of the breakers. Signal inputs to the OR gates are the trip signals from other various relays that can trip the breakers.

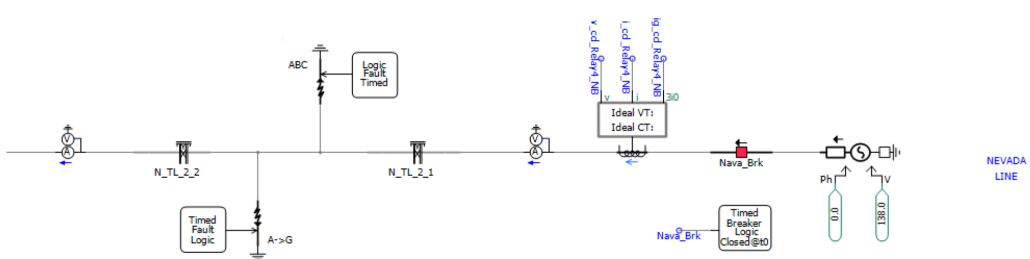
Nevada Line Faults

Nevada Line Big Picture

Due to time constraints the Boone's distance relay was not completed. This means that the 87L scheme setup for the Boone line is essentially copied over to the Nevada line and its breakers.


NAVADA
LINE
Ideal VT:
Ideal CT:
CT: Ideal
VT: Ideal
Timed
Breaker
Logic
Logic
Fault
Timed
Timed
Fault
Logic
ABC
A->G
N_TL_2_2
N_TL_2_1
Nava_Brk


i_cd_Relay1_B3
i_Navada_bus
i_cd_Relay1_B2
testsig
i_cd_Relay4_NB
Nava_BRKA
BRK1
BRK2
0
(3)
i_cd_Relay4_NB
I1
I2
i_Navada_bus
87L
vabc_B3_4
V1
V2
vabc_B2_1
Trip
Differential
Relay
0
Nava_Brk
TrpA3
B4fail_bopn
B3
Trp_ank
B1fail_bopn
B2


ABC
Logic
Fault
Timed
v_cd_Relay4_NB
i_cd_Relay4_NB
iq_cd_Relay4_NB
3i0
Ideal VT:
Ideal CT:
N_TL_2_2
N_TL_2_1
Nava_Brk
Ph
V
0.0
180.0
NEVADA
LINE
Timed
Fault
Logic
A->G
Nava_Brk
Timed
Breaker
Logic
Closed@t0

Breakers That Successfully Operated During Fault:

C. Nava_Brk

a. Operation:

➢ Boone_Brk trips if there is a fault on the Nevada line cutting power from the remote substation. If the current differential relay measured the feed current from boone does not match the measured feed from the Ames substation the breaker trips.

D. B3 & B2

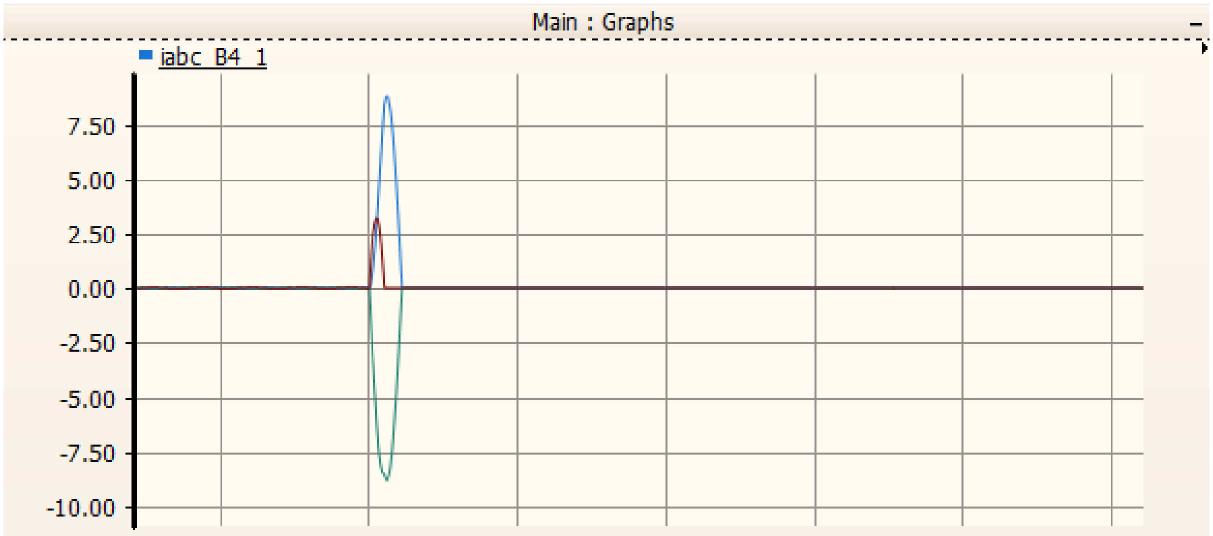
a. Operation:

➢ B3 & B2 trip for the Nevada line due to the ring bus configuration. To fully isolate the line we see the current differential relay is set to trip both breakers.

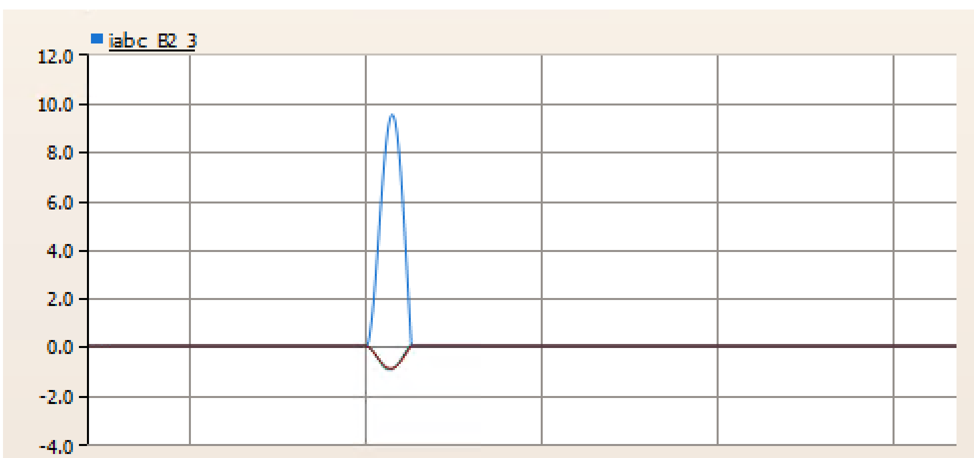
❖ **Steps in Fault Isolation**

➢ **Fault Detection:** The relay at Nava_Brk detects the fault on the Nevada line by observing the current does not match the measured current on the Ames end of the line. The 87L relay sends trip signals to the 3 breakers. In practice these signals are sent through an optical ground wire with one relay on each end of the line that coordinate with each other. To simplify the circuit in PSCAD one 87L relay is used with trip signals sent to each breaker from one trip signal.

Current Fault Behavior (3PH Fault @ 50% Line Length)



Current Fault Behavior (Single Phase to ground A-G @ 50% Line Length)



1. **Current Before Fault**

   a. **Observation:**

      - Before the fault occurs, the current in all three phases (A, B, and C) is at a steady state and near zero. This indicates a no-load or light-load condition in the system. There is no abnormality in the current flow across the phases.

b. **Reasoning:**

   - Under normal operating conditions, the system is balanced, and no fault exists. The current is minimal, and the relay monitoring does not detect any unusual activity.

2. **Current During Fault**

   a. **Observation:**

   - When the single-phase-to-ground fault occurs, there is a sharp spike in the current of one phase (likely Phase A based on the graph), which reaches a magnitude exceeding 9.5 per unit (pu).
   - The current in the other two phases (B and C) remains unaffected and close to zero.

   b. **Reasoning:**

   - The fault introduces a low-impedance path between the affected phase and the ground. This causes a rapid increase in current for the faulted phase.
   - The other phases remain unaffected because the fault is isolated to one phase (single-phase-to-ground fault).
   - The faulted current is detected by the relay, which identifies the abnormal rise and sends a signal to the associated breaker.

3. **Current After Fault**

   a. **Observation:**

   - After the breaker trips to isolate the fault, the current in the faulted phase drops back to near zero. The unaffected phases remain stable and close to zero throughout the event.

b. **Reasoning:**

- The breaker (e.g., Nevada_Brk) isolates the faulted section, preventing further current flow into the fault.
- The system stabilizes as the fault current is interrupted, and the healthy phases maintain their steady state without disruption.

4. **Characteristics Fault**

a. **Faulted Phase Behavior:**

The faulted phase experiences a sharp and transient increase in current magnitude due to the low-impedance path.

The spike in current is an immediate and clear indication of a fault condition.

b. **System Recovery:**

The fault is cleared by the tripping of the breaker, and the current in the faulted phase returns to zero.

The protection system ensures that the fault does not propagate to other sections of the power system.

5. **Protection Mechanism**

a. **Relay Detection:**

The relay (e.g., SEL-411L or SEL-421) detects the high current in the faulted phase and determines the location of the fault using 87L (Line Current Differential Protection) or other backup protection schemes (e.g., distance protection).

b. **Breaker Operation:**

The breaker associated with the faulted line (e.g., Nevada_Brk, B2, and B3) trips immediately upon receiving the relay signal, isolating the faulted section.

c. **System Stability:**

The tripping of the breaker prevents the fault current from flowing further, protecting system components and maintaining stability.

Relays that operated for Boone Line Fault

1. **Primary Relay: SEL-411L**

   a. **Function:**

   - The SEL-411L relay is the primary protection relay for the Nevada line, implementing 87L (Line Current Differential Protection).
   - It compares the currents entering and leaving the Nevada line. If there is a mismatch, it identifies a fault within the line.

   b. **Operation:**

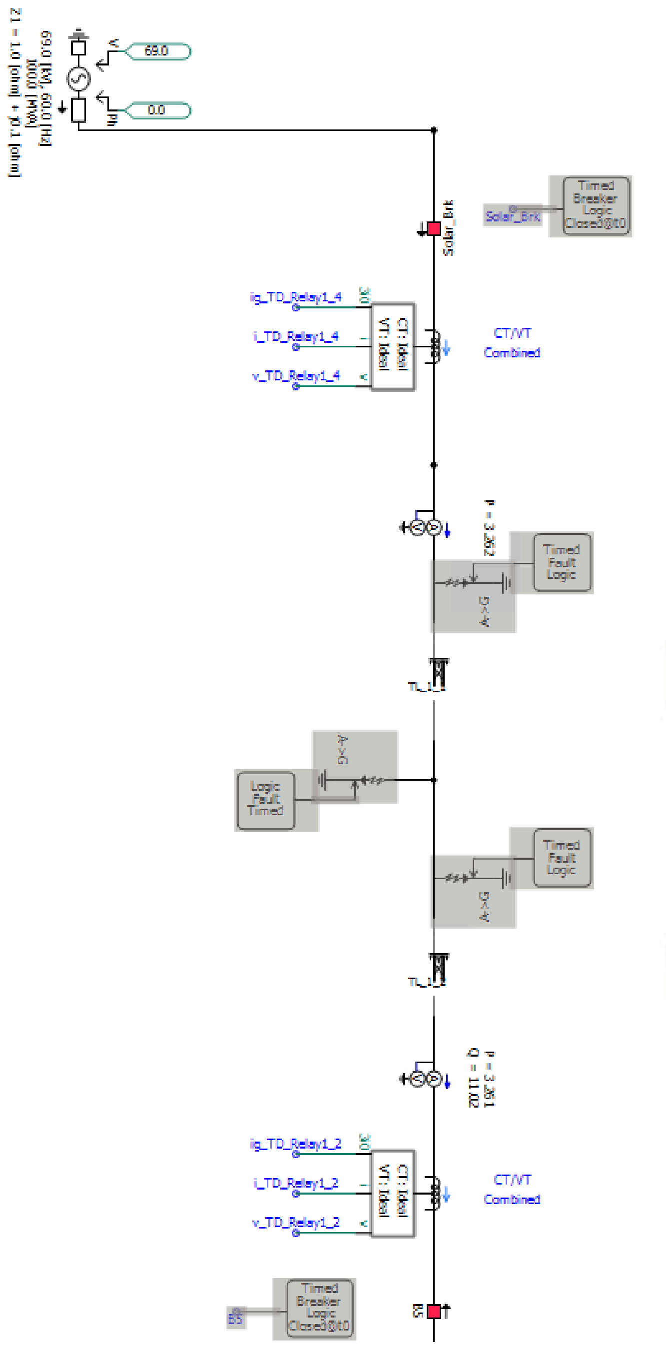
   - Detects the fault and sends a trip signal to Nevada_Brk, B3, and B2.

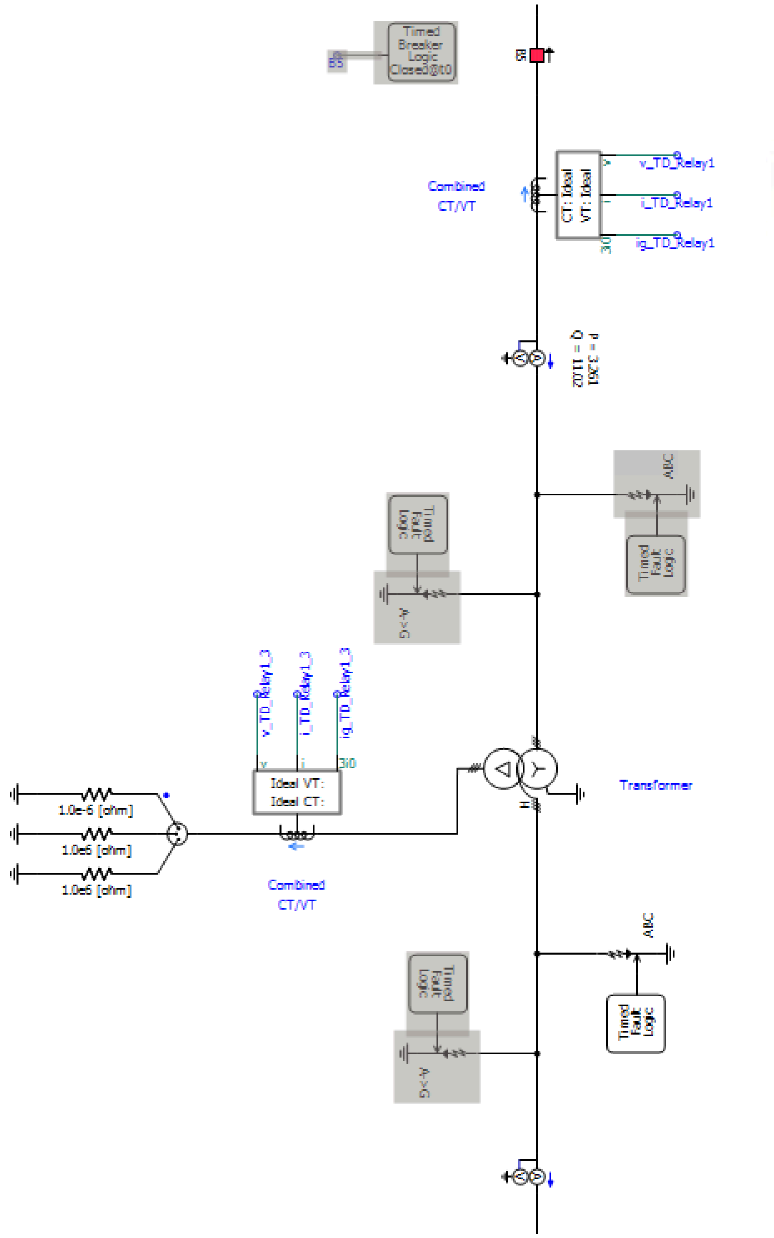
2. **Relay Communication and Coordination**

   - The 87L protection scheme ensures that the fault is detected accurately and quickly by comparing currents at both ends of the Nevada line.
   - If the primary protection (SEL-411L) fails.

Solar Farm Line Faults

Solar Farm Line Big Picture





Breaker Operations for Fault scenarios on Solar Farm Line

Fault Scenarios

1. **Fault on the Transformer**: This includes faults on either the high-voltage (HV) or low-voltage (LV) side of the transformer connected to the Solar Farm line. The transformer section is protected by B5, B4, and B3.

a. The relay that protects this zone works slightly differently because of the transformer. To ensure that the faults are detected properly the ratio of the transformer must be accounted for in the transformer zone.

b. The transformer differential relay works just like the line differential relay except that it adjusts the per unit current calculation based on the different current levels caused by the transformer.

c. This relay should also be used for montering currents on the neutral and tertiary winding as this must be taken into consideration for the total current.

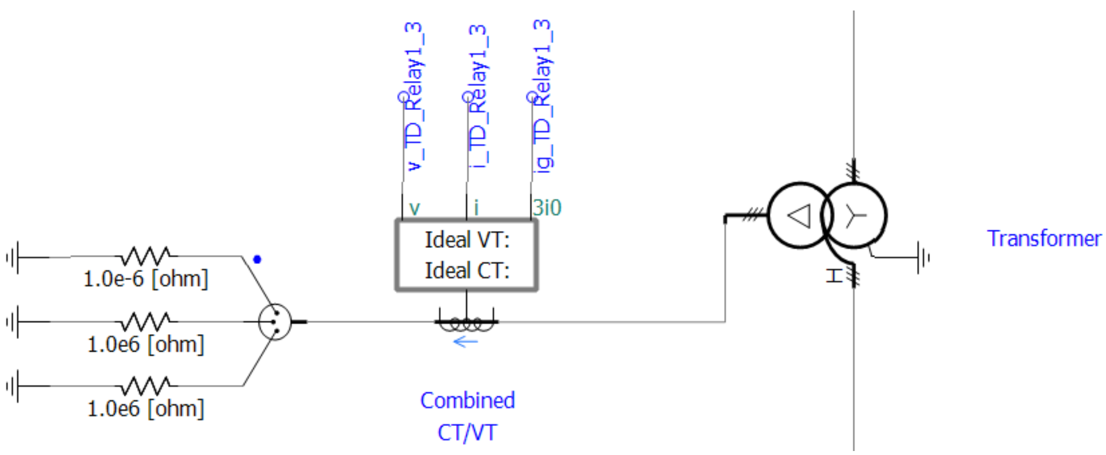


Figure shows the CT montering the current on the delta connected tertiary of the transformer.

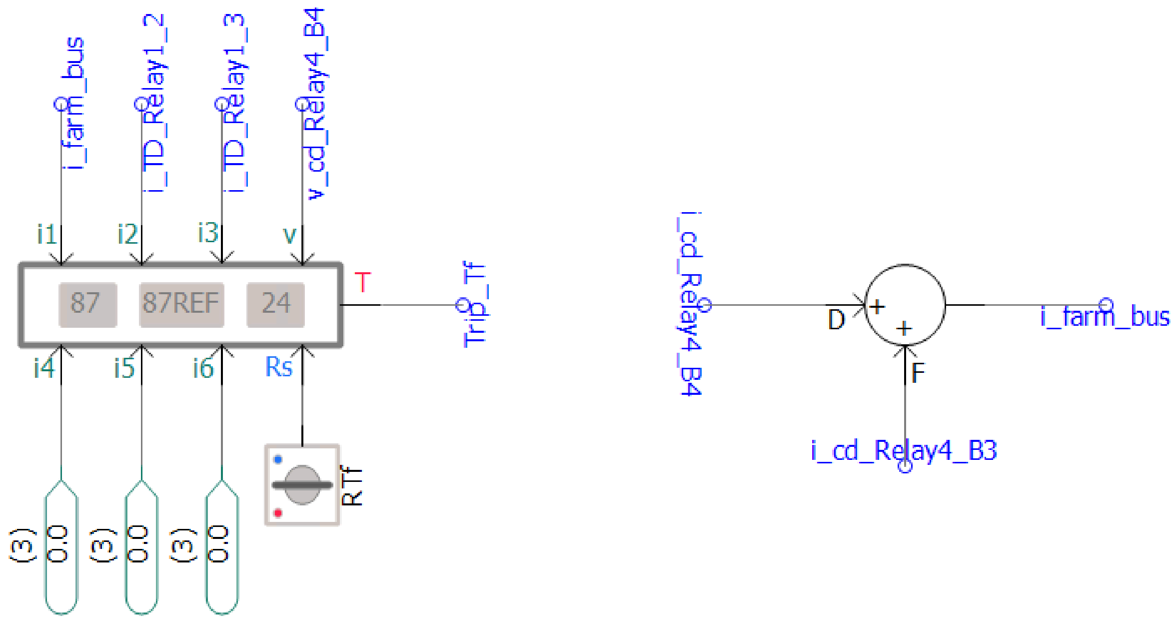


Figure shows the transformer differential relay and the sum block used to sum currents measured bus breaker CTs 4 and 3.

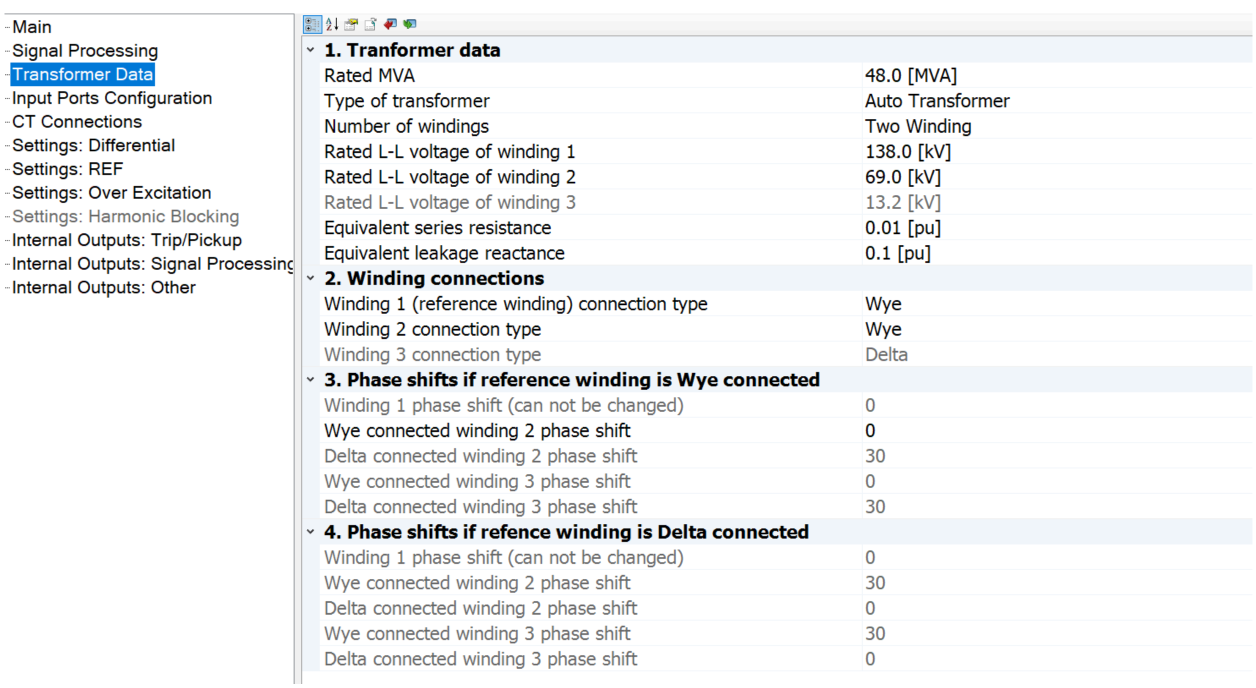


Figure shows the transformer differential relay and how it can be configured for various transformer types and ratios.

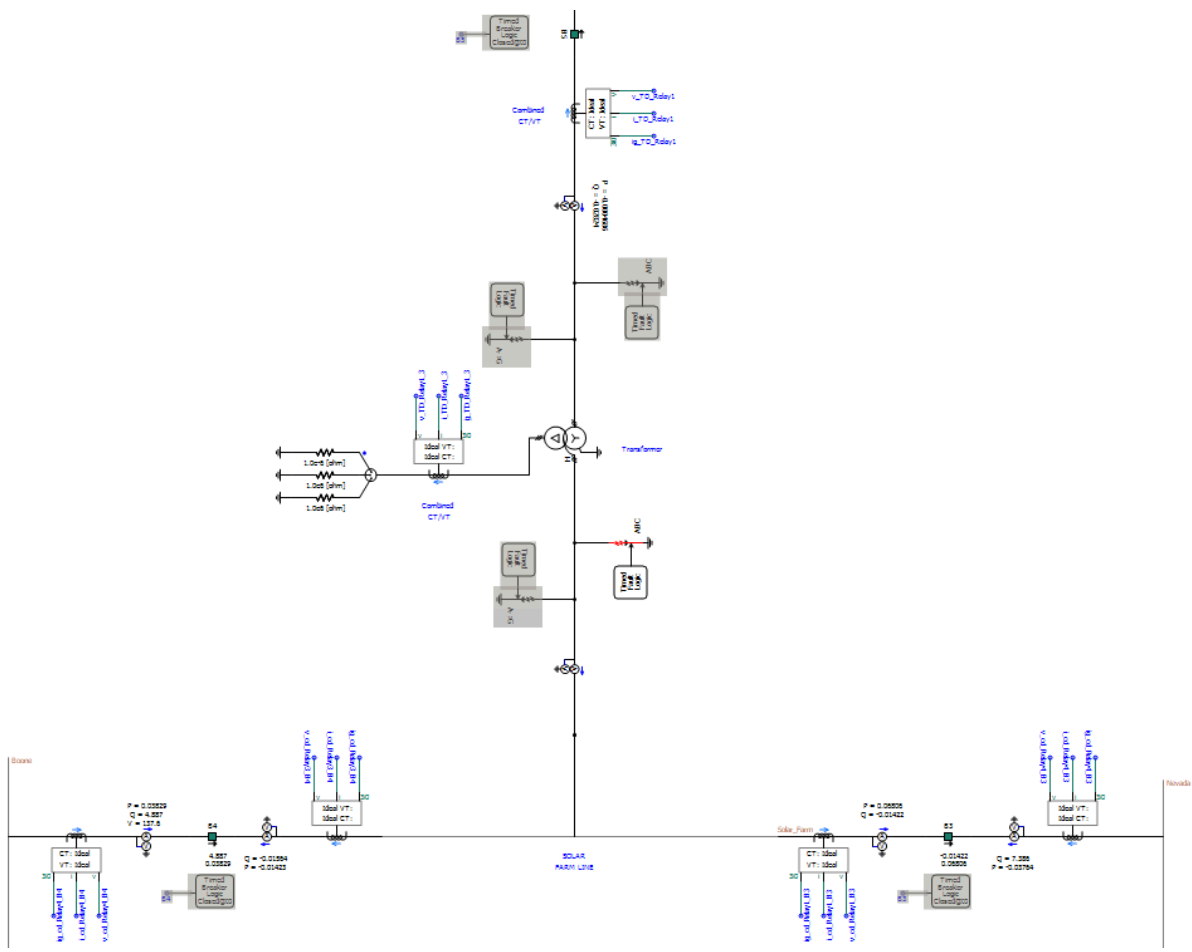


Figure shows a 3 phase fault on the high voltage side of the transformer. The transformer differential relay tripped and successfully opened B5, B4, and B3. No other breakers operated.

2. **Fault on the Transmission Line**: This includes faults on the Solar Farm transmission line, which is protected by Solar_Brk and B5.

    a. The relay used to protect this zone is the line differential. Because B5 is inline with the solar farm transmission line there is no need to sum two currents before connecting to the relay.

    b. The relay provides an option for voltage inputs, but these values are not necessary for this relay and are unused.

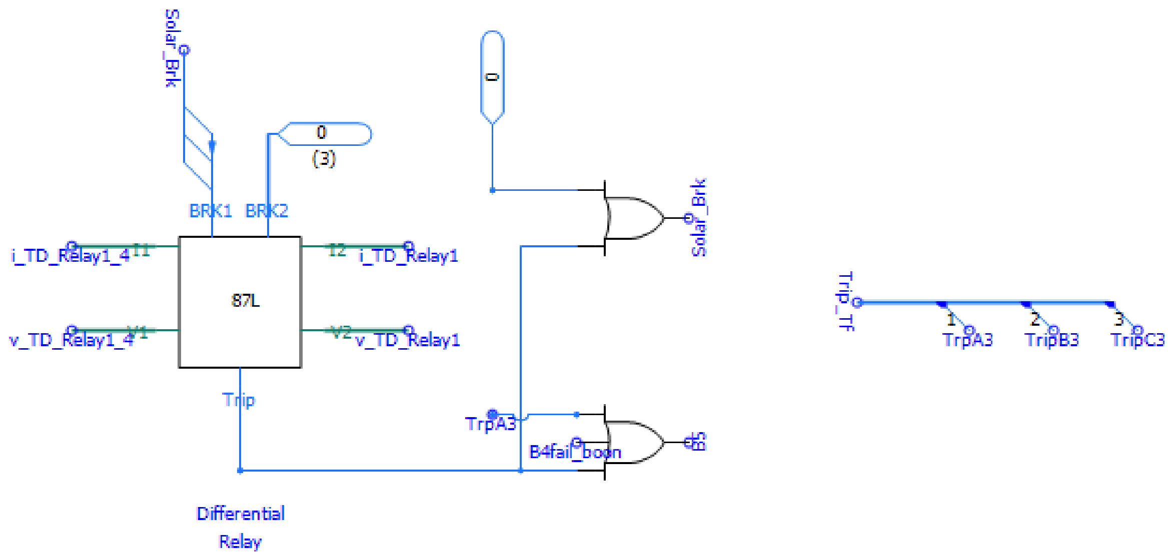
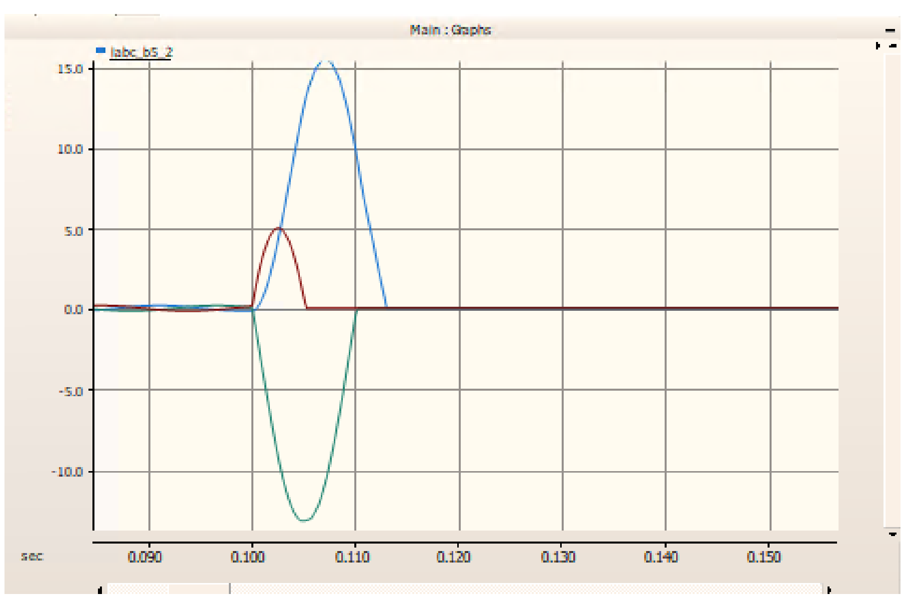
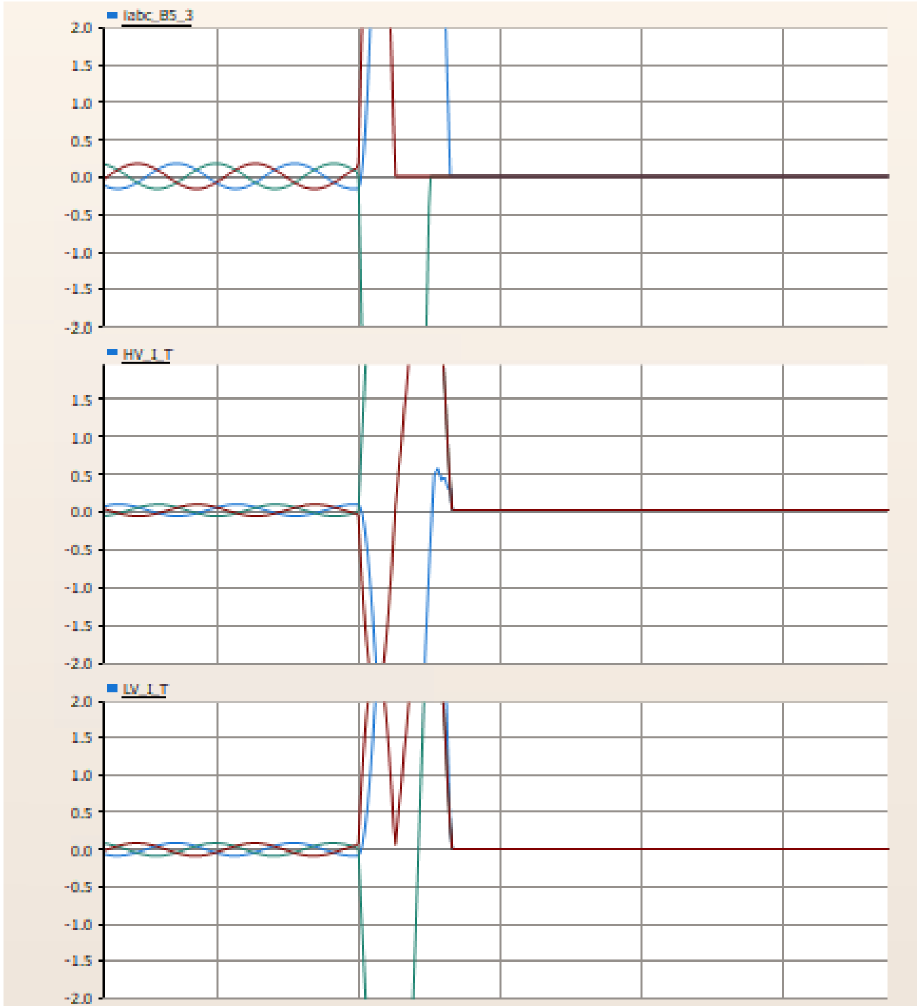


Figure shows the solar farm 87L relay.

Current Fault Behavior (Three phases ABC Transformer Low Voltage Side)





1. **Current on B5**

   a. **Before Fault:**

      - The currents on all three phases (red, blue, and green curves) are sinusoidal, balanced, and consistent in magnitude. This indicates normal operation, with no abnormalities in current flow through B5.

   b. **During Fault:**

      - When the fault occurs: A sharp spike is observed in the faulted phases, representing the fault current flowing through B5.

c. **After Fault**

- After B5 trips, all currents (red, blue, and green) drop to zero, confirming that B5 successfully isolates the faulted transformer from the Solar Farm line.
- This complete current interruption shows that the fault is cleared.

2. **Current on Transformer High Voltage side**

a. **Before Fault**

- All three phases show sinusoidal, balanced currents, indicating normal operation on the high voltage (HV) side of the transformer.

b. **During Fault:** When the fault occurs:

- The three phases experiences a significant current spike due to the low-impedance fault path between the phases
- This reflects the fault current flowing through the HV side of the transformer into the faulted path.

c. **After Fault**

- After B5, B4, and B3 trip, the fault current is interrupted, and all phases drop to zero.
- This confirms the fault is isolated on the HV side of the transformer, and no further current flows into the faulted path.

3. **Current on Transformer Low Voltage side**

a. **Before Fault:**

- The currents on all phases are sinusoidal and balanced showing normal operation on the low- voltage (LV) side of the transformer.

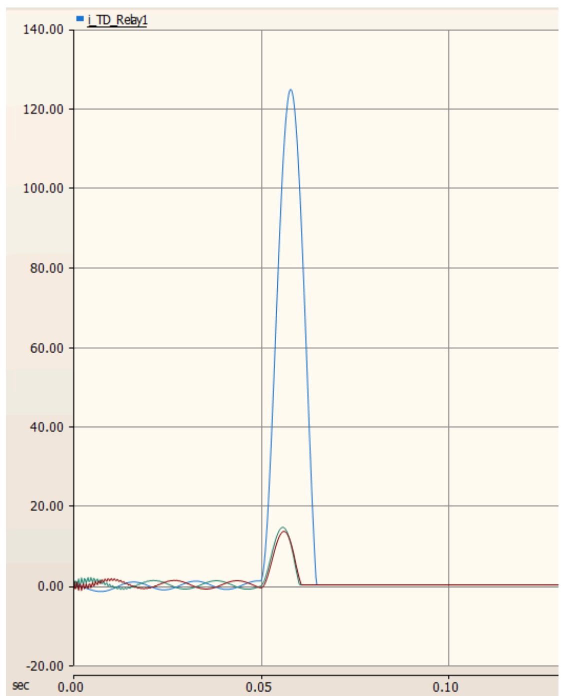
b. During Fault:

- The faulted 3 phases give rise to high currents as the 3 phases are shorted together.

c. After Fault

- The current again goes to zero as all paths for current are disconnected from their sources.

Current Fault Behavior Solar Farm Line Zone (SLG A-G @ 50% of Line Length)



4. **Current on B5**

a. Before Fault:

- The currents on all three phases (red, blue, and green curves) are sinusoidal, balanced, and consistent in magnitude. This indicates normal operation, with no abnormalities in current flow through B5.

b. **During Fault:**

- When the fault occurs: A sharp spike is observed in the faulted phases, representing the fault current flowing through B5.

c. **After Fault**

- After B5 trips, all currents (red, blue, and green) drop to zero, confirming that B5 successfully isolates the faulted transformer from the Solar Farm line.
- This complete current interruption shows that the fault is cleared.

Breaker B5 and Solar_Brk both opened isolating the fault and the solar farm line while leaving the rest of the circuit operating as expected only the line differential relay tripped.

Breaker Failure Testing for B4

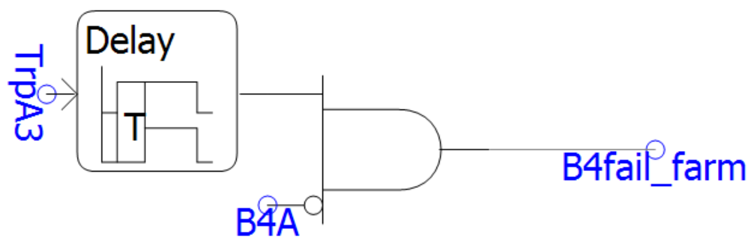
The Breaker failure relay was not provided with the protection library. To model the breaker failure relay the logic was determined using a truth table and implemented for breaker B4. This logic could easily be transferred to all of the other breakers as the concept is the same for each. A slight modification would be needed to account for cascading breaker failures, but the concept would be the same.

Breaker Failure Logic Table:

Breaker Trip Signal Received from Relay	Breaker Position	Breaker Failure Occurred
0	0	0
0	1	0

1	0	1
1	1	0

Signal logic in PSCAD using an and gate with one terminal inverted:



A .025 second delay is added to the trip signal accounting for breaker operation delay.

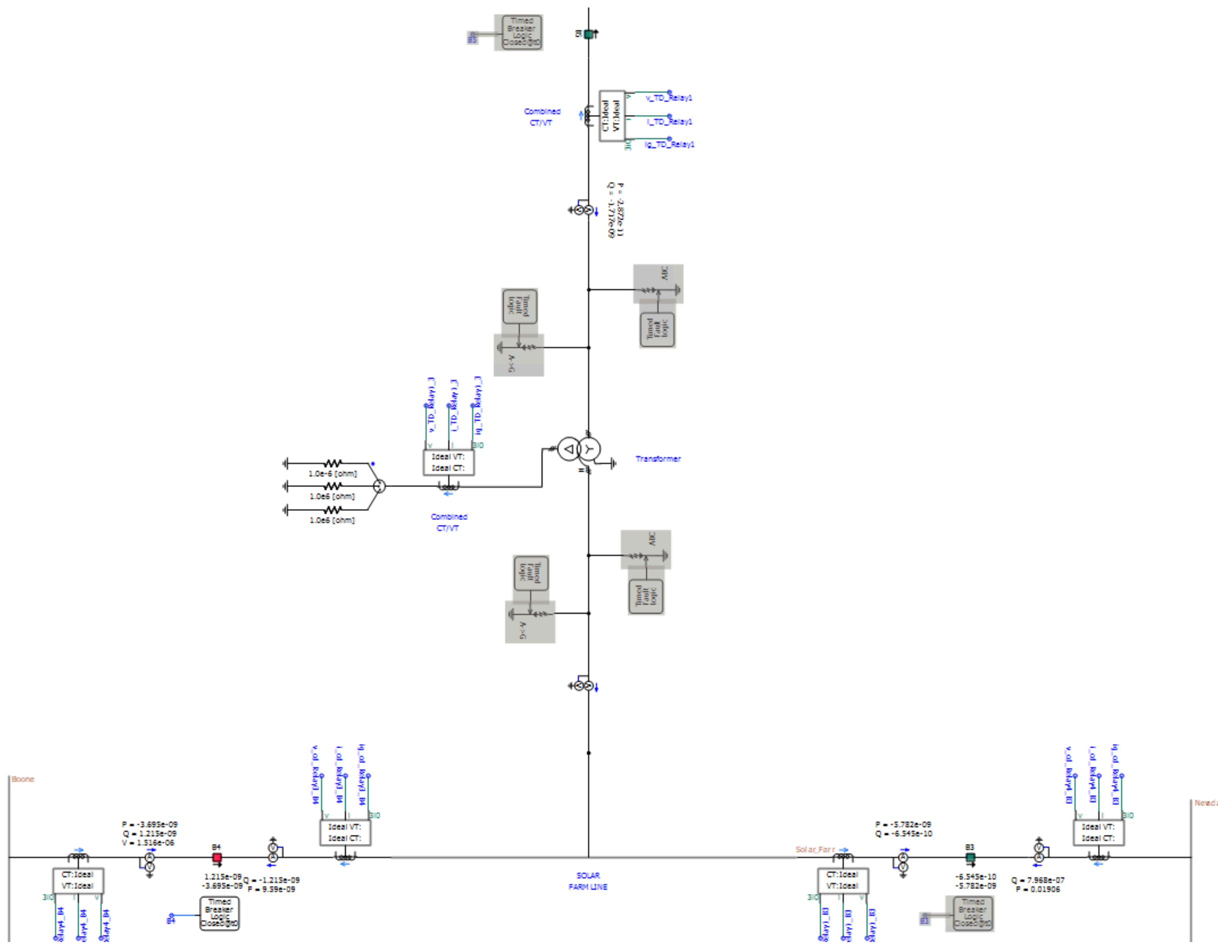
Signal B4A is the breaker B4 position. TrpA3 is one of the trip signals from a relay that normally trips breaker B4.

Transfer Trips Intended:

- For Fault on Transformer Section
  - Boone_Brk
  - B1
- For Fault on Boone Line
  - B5
  - B3

Operated as expected:

When there is a fault on the Boone Line or the Boone Bus segment, but B4 operation is disabled simulating a breaker failure the transfer trip logic successfully initiates a trip of the adjacent breakers.



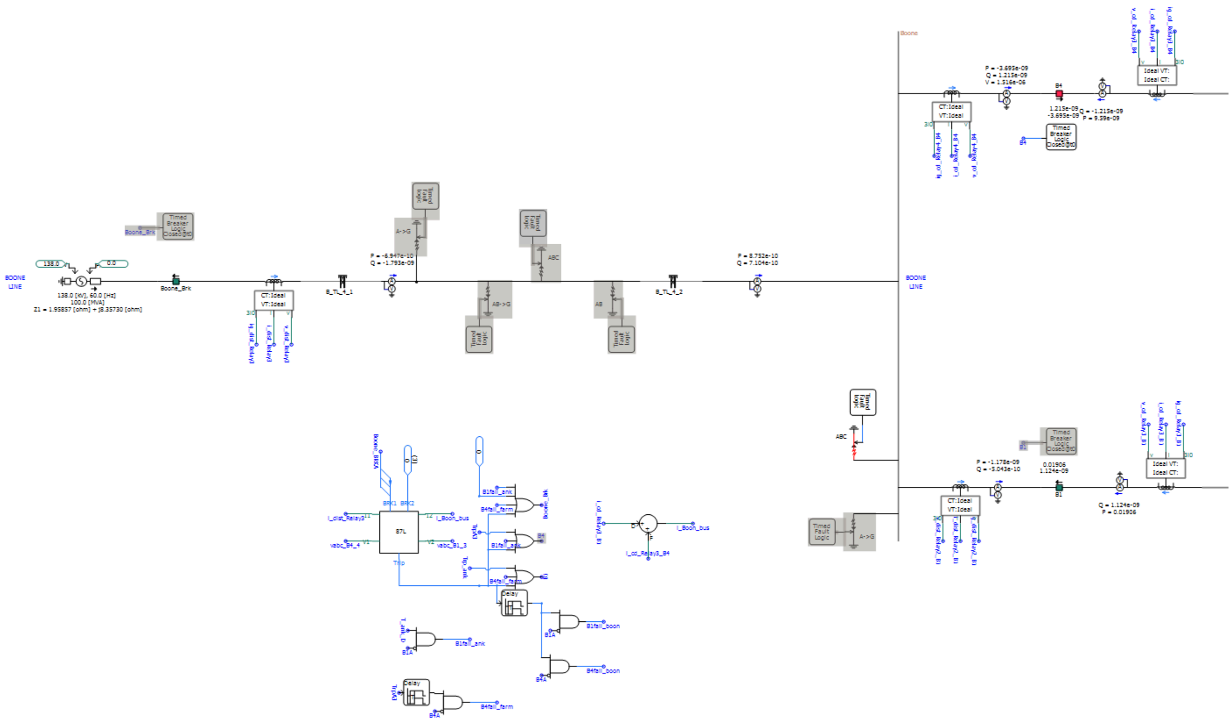


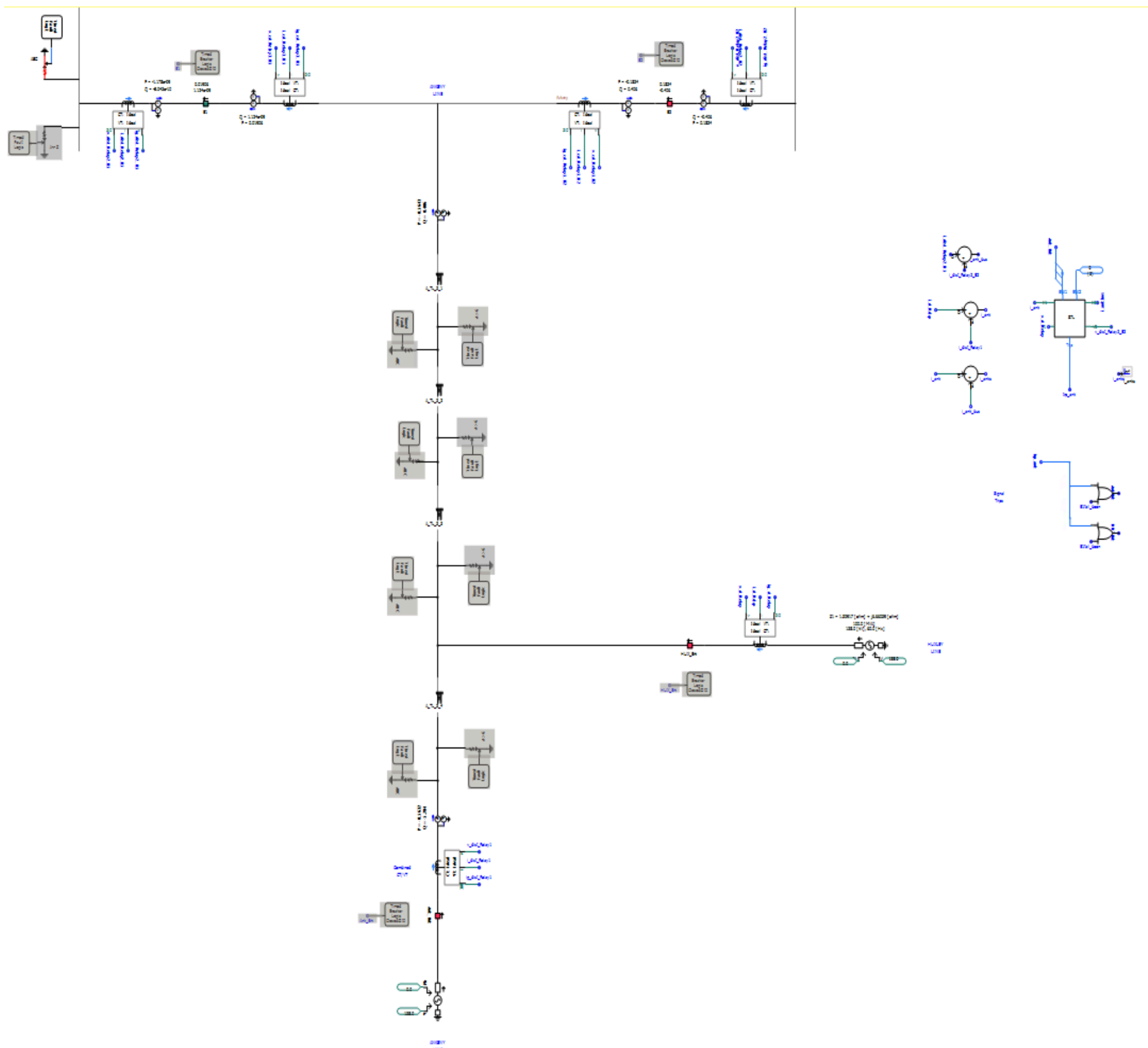
Figure shows the DTT for B4 failure with a fault in the Transformer Zone.

As seen in the figure above Breakers B5 and B3 trip to clear the fault on the bus that breaker B4 was unable to due to the disabled operation for that breaker. This shows the function of the transfer trips in a Boone line fault scenario, but there also needs to be a different set transfer trips for a fault on the Solar Farm transformer Zone.

The figure shows the breakers which turned green indicating they opened successfully. As intended the transformer zone was extended to include the Boone line due to the Breaker failure at Breaker B4.

Ankeny Line Faults

Ankeny Line Big Picture



Breakers That Successfully Operated During Fault:

E. **Ank_Brk & Hux Brk**

a. **Operation:**

- ➢ Ank_Brk and Hux_Brk trip if there is a fault on the Ankeny line cutting power from the remote substation. The Zone One (1) phase to ground pickup activated on the distance relay for ankeny. Zone One (1) is configured to instantaneously trip the local breakers.

F. **B2 & B1**

a. **Operation:**

- ➢ B2 & B1 trip for the ankeny line due to the ring bus configuration. To fully isolate the line we see the current differential relay is set to trip both breakers. This fault is at 100% of the line length and should be outside of this relay's Zone One (1) distance protection, but if we track the Zone One (1) pick up the relay incorrectly picks up this fault as if it is in Zone One (1) instantly tripping it.

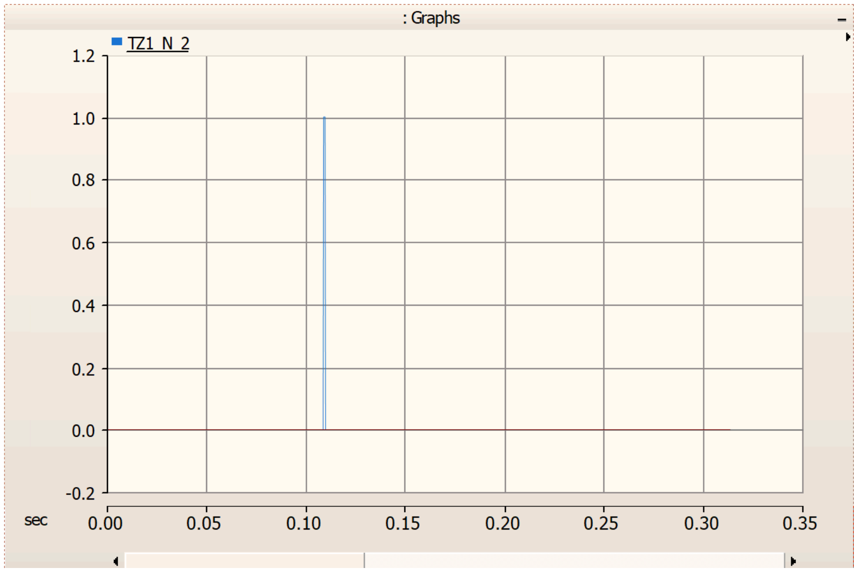


Figure shows plot of the Zone One (1) pickup for the local substation distance relay.

This failed operation of Zone One persists if any of the other faults are run for the other lines making the distance relays over trip extensively. To show that this problem goes away by reducing the Zone one Right resistive reach for the relay the Zone two (2) pick up trips the relay .3 seconds following the fault.

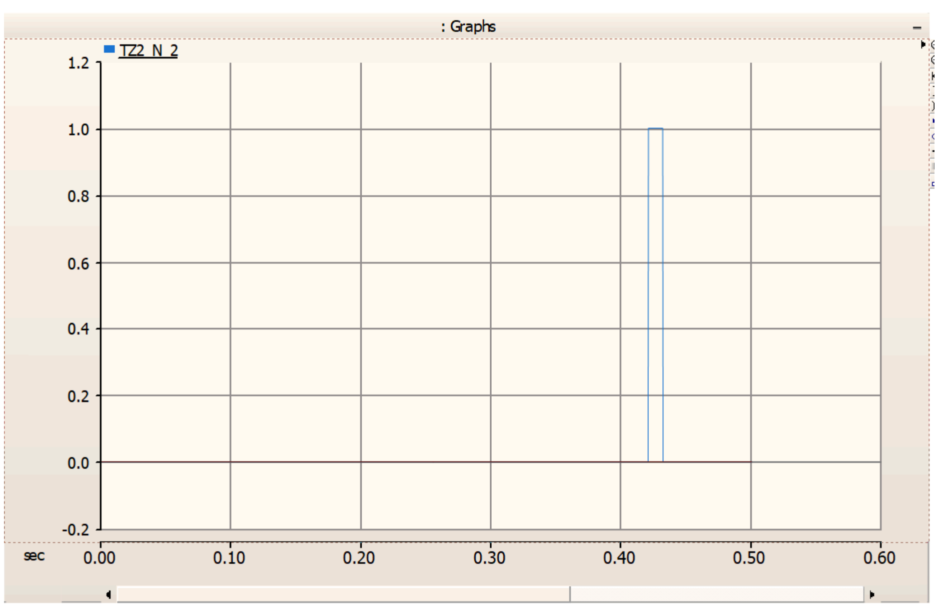


Figure shows Zone two (2) pickup for Ames- Ankeny distance relay

Further analysis of the circuit and relay settings is needed to identify what the best impedance values should have been selected for the line. Ideally the new values should be smaller than the current selected values as the Zone One (1) relay is clearly over reaching. The current relay calculations were done using MATLAB. The formulas were taken from the SEL relay manuals and specific details of the distance relays used in PSCAD can be found in Appendix A.

Relay Settings Calculations

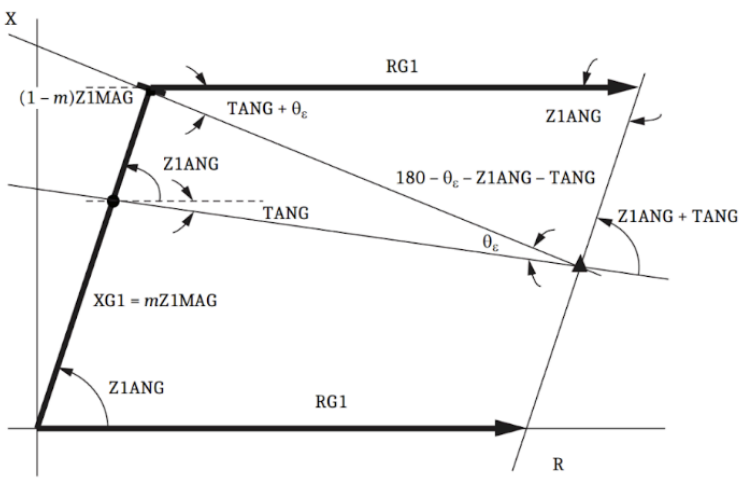


Figure 6.4 CT and VT Composite Angle Error Evaluation for Zone 1 Resistive Reach

For increasing RG1, the intersection with the Zone 1 reactive line is the indication of $RG1_{MAX}$, the maximum secure resistive reach setting for Zone 1. Using the law of sines and trigonometry, you can calculate $RG1_{MAX}$ by considering the per-unit reach *m* of the Zone 1 reactance XG1 and the PT and CT composite angle error θ_{ε} by using *Equation 6.17*.

$$RG1_{MAX} = \frac{\sin(\theta_{\varepsilon} + Z1ANG)}{\sin(\theta_{\varepsilon})} \cdot (1 - m) \cdot Z1MAG$$

Equation 6.17

Figure shows the relay calculation used for determining the Zone one right resistive reach that is causing over reaching for the relay. [1]

The MATLAB script shows the implementation of this formula to obtain the relay settings.

```
%% ground ankeny end
thetaerr = 2; % error correction angle (degrees)
tilt = -6; % non-homogenious angle (degrees)
Z1ang = 76.88; % positive sequince line impeadance (degrees)
RCA = Z1ang + tilt;
mL = .1;
m = .8; % negitive sequince line impeadance
nct = 160; %ct ratio
npt = 1200; % vt ratio
Ns = nct/npt; % transformer ratio
Z1MAG = 19.393 * Ns;
trig = (sind(thetaerr + Z1ang + tilt)/sind(thetaerr));
RRR = (sind(thetaerr + Z1ang + tilt)/sind(thetaerr)) * (1-m) * Z1MAG; %right resistive reach
ZRF = Z1MAG * m; %forward reach impeadnace mag
LRR = Z1MAG * mL; %left resistive reach
%Ip = (.72*cosd(Z1ang) + .72*sind(Z1ang)*1j) *(cosd(6)+sind(6)*1j);
```

Explanation of each Variable calculation:

1. The tilt angle or non-homogeneous angle: was determined by simulating a fault on the line in PSCAD and measuring the difference in phase angle between the line current and the fault current.
2. Z1ang was found using PSCADs Solve Constants for the transmission line which provided the positive sequence impedance in the output after configuring the transmission line based on data provided by Burns and McDonnell.
3. The variable m represents the Zone One (1) reach which should have been set to 80% of the line's impedance.
4. The transformer compensation ratio Ns is needed for the relay to accurately determine the impedance as it will be scaled by this value due to the transformer ratios used to measure the current and voltage.
5. The Comparator angle was assumed to be 90% as this binder is used for the reverse reach element (see Appendix A).

6. Left resistive reach was assumed to be 10% of the line positive sequence impedance to ensure that Zone One (1) fully overlaps with Zone Two (2) and Zone Three (3).

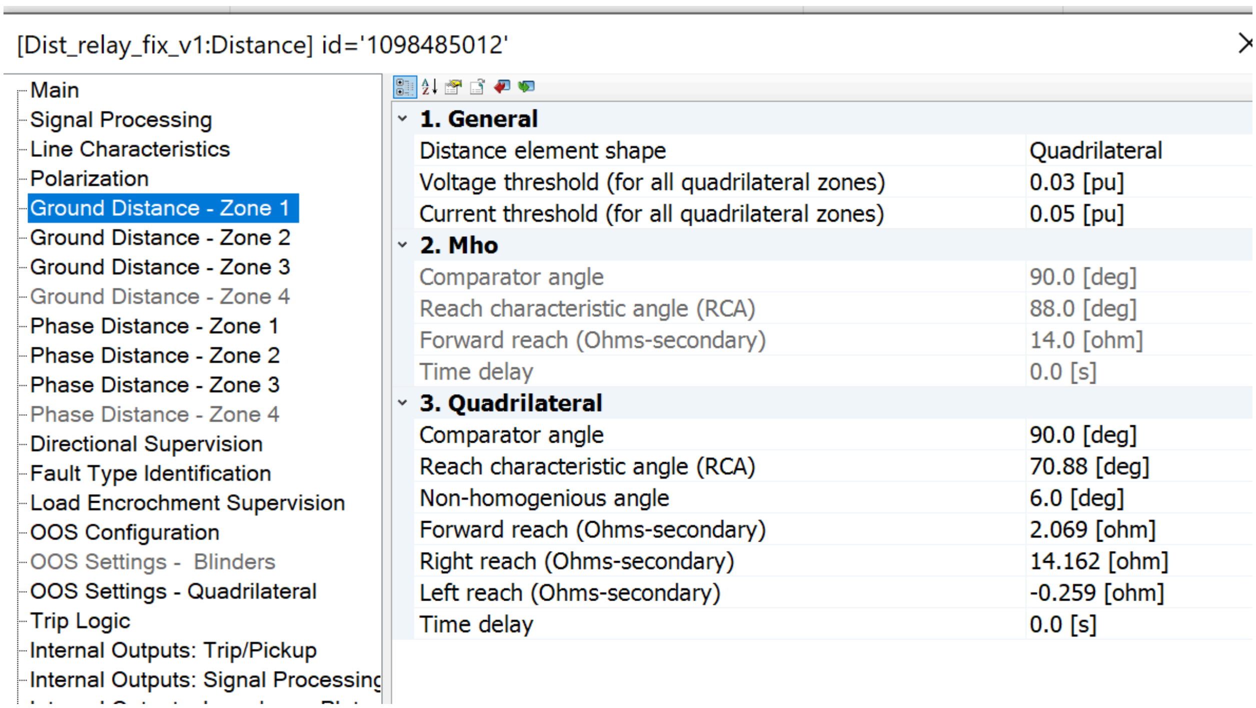


Figure showing final relay settings for Zone One (1)

A similar approach was used for the calculation of Zone Two (2) impedances however 120% of the impedance Zone for Zone One (1) was used instead of 80% of the line impedance. A time delay of .3 (s) was used to account for the time needed to send a Blocking signal from the remote distance Relay.

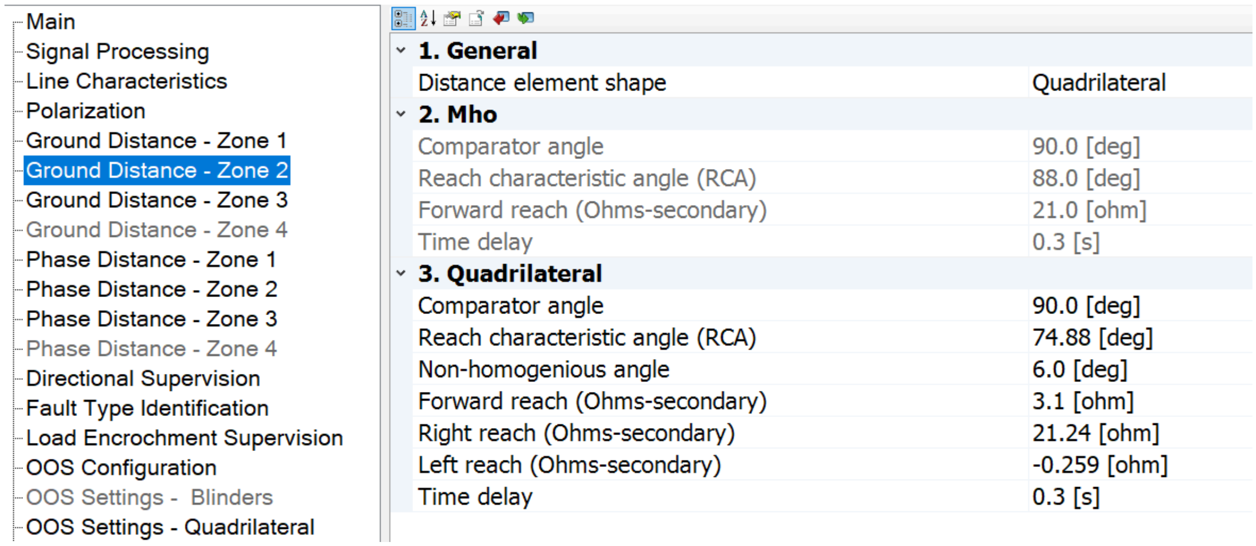


Figure shows the Zone Two (2) settings

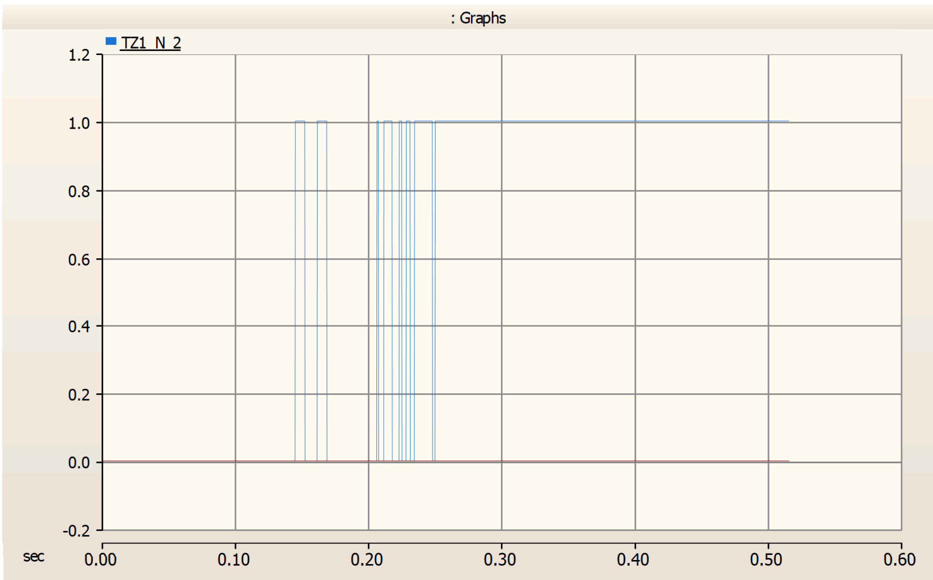
Over Tripping problems:

Breaker B1 and B2 are tripping on faults outside of the ankeny line because the ankeny distance relay is tripping the bus end of the line. Despite changing the left reach impedance all the way down to 0 the problem still persists. This means the Ankeny line is isolated from the system when it does not need to be. The Ankeny and Huxely Breakers remain untripped because the fault is outside of its relays Zone of protection.

Possible solutions to try if there was more time:

1. Check the current and voltage measurements. One issue that may be causing this error is if the measured values are reported as Volts or Amperes, but are actually in per unit.
2. Try tuning the Zones to prevent over and under tripping through trial and error by plotting the impedance calculated by the relay for each fault then setting the Zones accordingly.

3. For the phase to phase faults more research would be needed to properly calculate these Zones.



Plot of Zone One (1) trip signal with external fault.

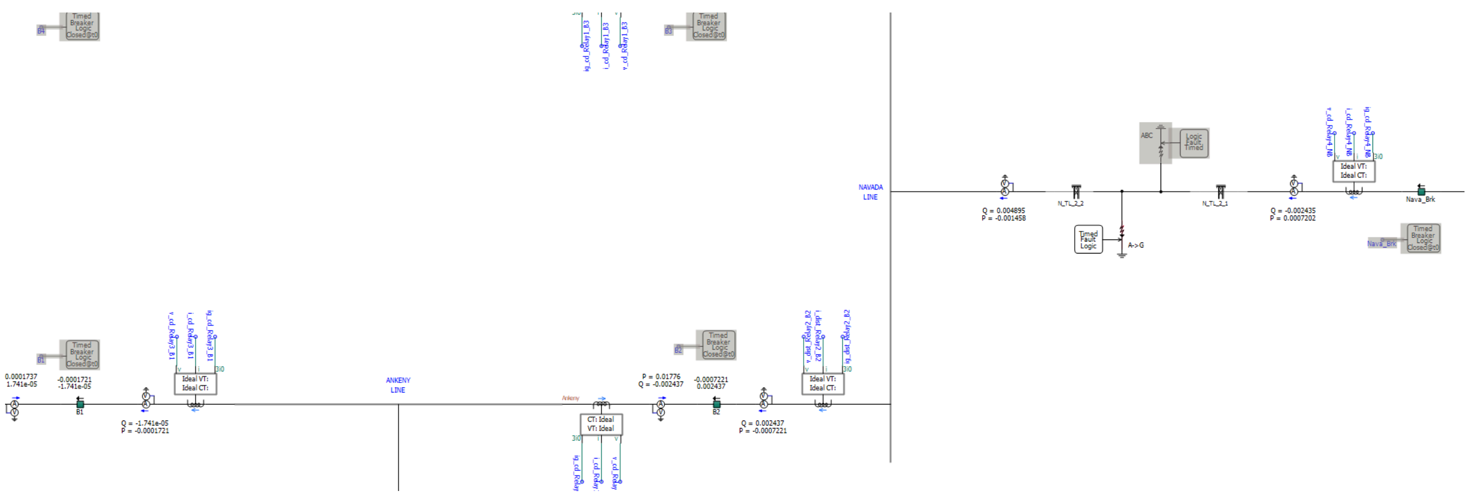


Figure shows over tripping of Breaker B1 for fault on Nevada line

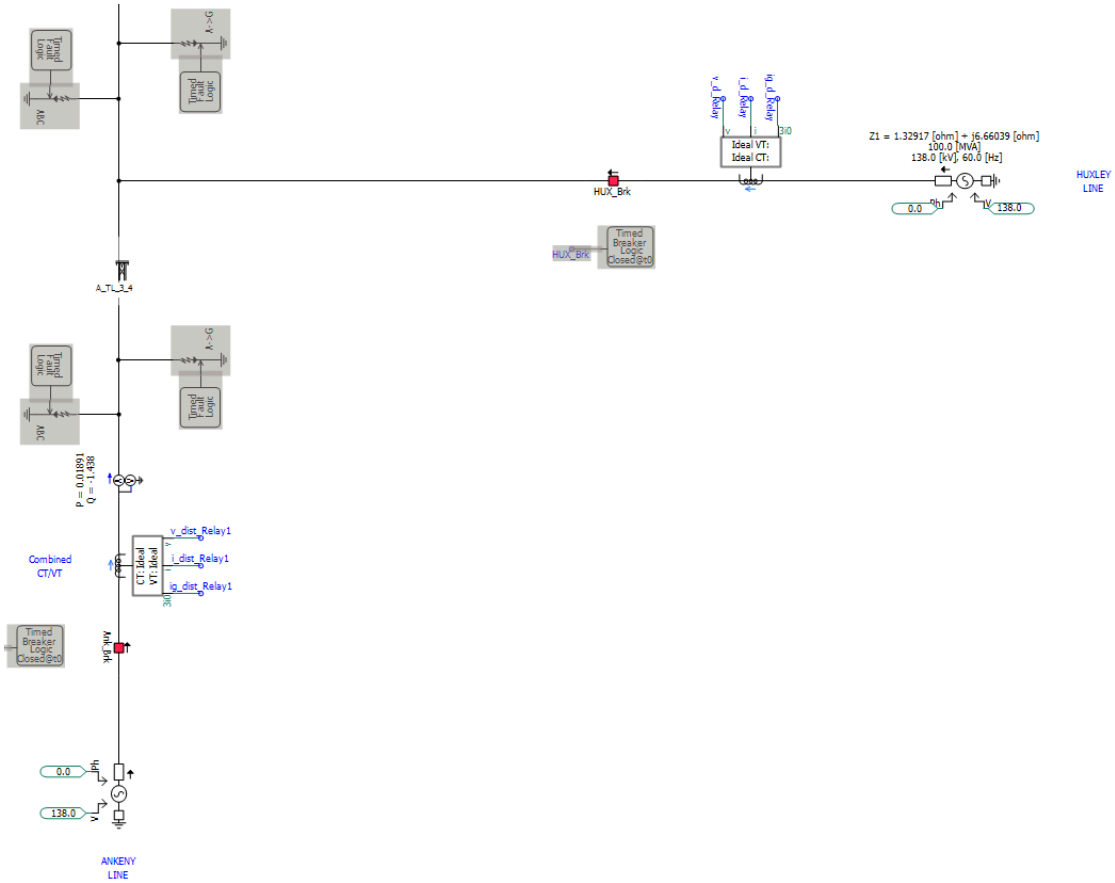


Figure shows the Zone One (1) and Zone Two (2) do not pick-up the Nevada line fault correctly, keeping the Ankeny and Huxley connection on-line.

Appendix A

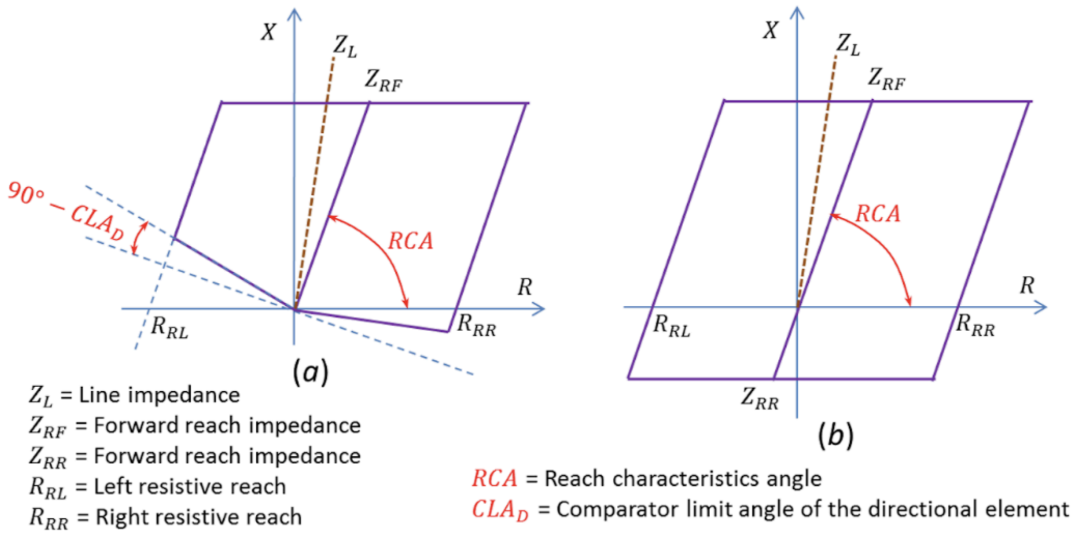


Figure 3 Quadrilateral characteristics (a) directional, (b) non-directional

REFER TO RELAYS MANUAL FOR MORE INFORMATION ON RELAY PROTECTION

Citations

[1] *SEL-411L Instruction Manual,* Schweitzer Engineering Laboratories, 2024.