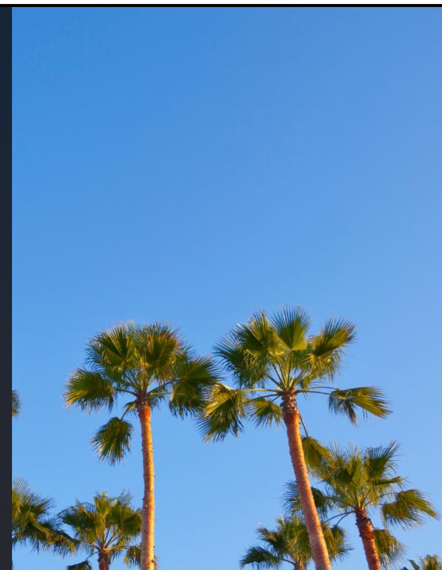
Simulating Intermittent Ground Faults in Petersen Coil Networks

Schweitzer Engineering Laboratories, Inc. (SEL)



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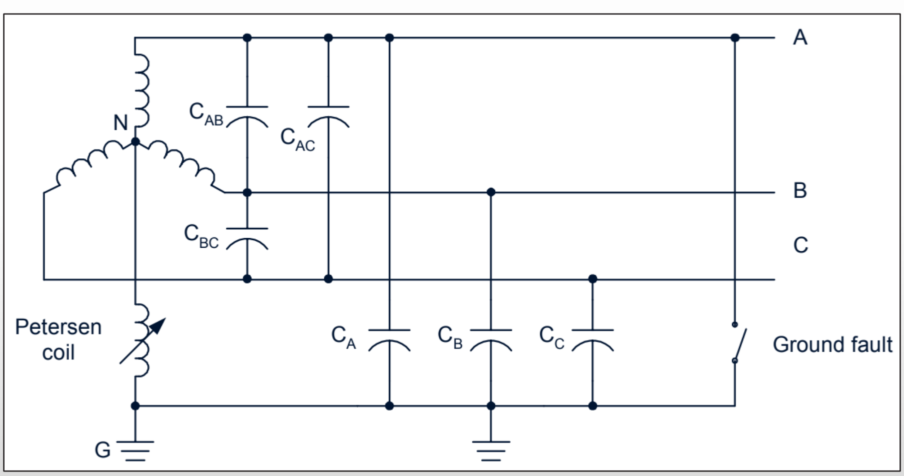
Agenda

- Compensated Grounded Systems
- Stable Ground Faults
- Intermittent Ground Faults
- Cable Modeling
- Petersen Coil Tuning
- Stable Fault and Intermittent Ground Fault Logic Model
- Python Automation Framework

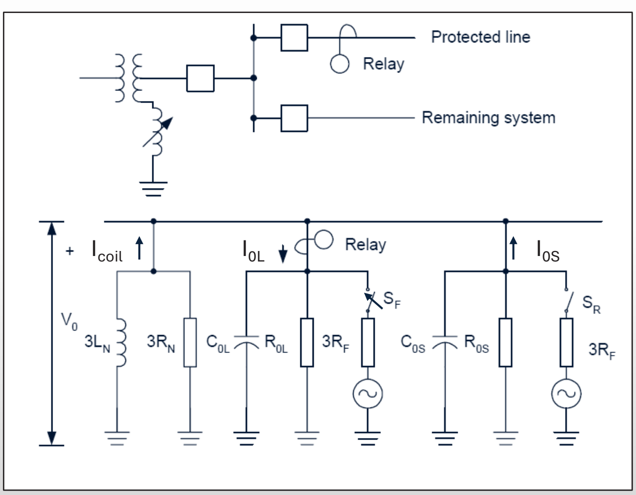
Compensated Grounded Systems

Simplified Network Representation



Stable Ground Faults

Zero-Sequence Representation



Forward Fault (close S_F):

$$I_{0L} = I_{coil} + I_{0s}$$

$$I_{0L} = -V_0\left(\frac{1}{3R_N} + \frac{1}{R_{0S}}\right) - jV_0\left(\omega C_{0S} - \frac{1}{3\omega L_N}\right)$$

Reverse Fault (close S_R):

$$I_{0L} = V_0\left(\frac{1}{R_{0L}} + j\omega C_{0L}\right)$$

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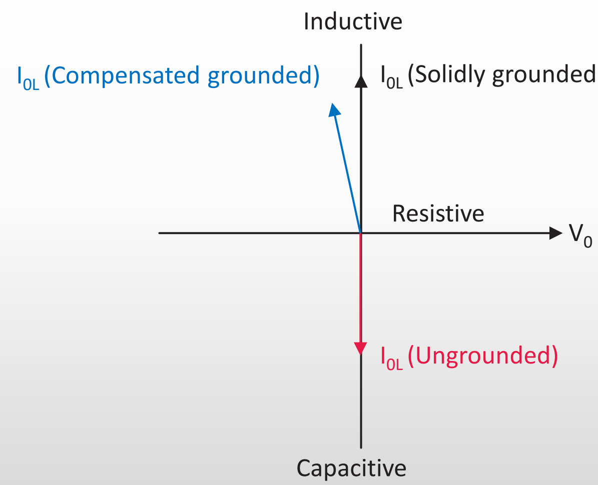
Phasor Representation

Forward Fault (close S_F):

$$I_{0L} = -V_0\left(\frac{1}{3R_N} + \frac{1}{R_{0S}}\right) - jV_0\left(\omega C_{0S} - \frac{1}{3\omega L_N}\right)$$



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Intermittent Ground Faults

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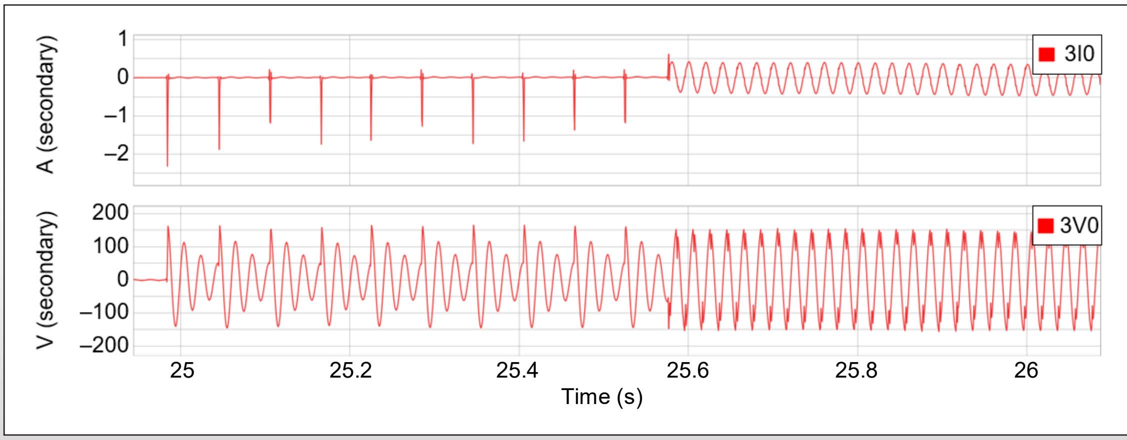
Real IGF Event



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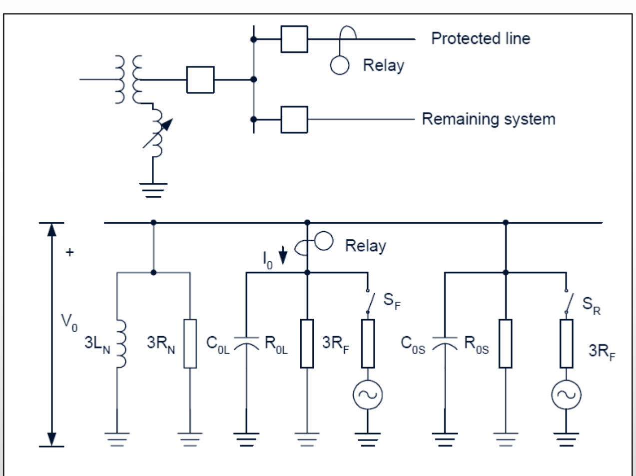
Zero-Sequence Representation



Forward Fault (close S_F):

$$i_{0L}(t) = -\left(\begin{array}{c} C_{0s}\dfrac{dv_0(t)}{dt} + \dfrac{v_0(t)}{R_{0s}} \\ + \dfrac{1}{3L_N}\displaystyle\int_{t_0}^{t} v_0(t)\,dt + \dfrac{v_0(t)}{3R_N} \end{array} \right)$$

$$i_{0L}(t) \cong -\left(C_{0s}\frac{dv_0(t)}{dt} \right)$$

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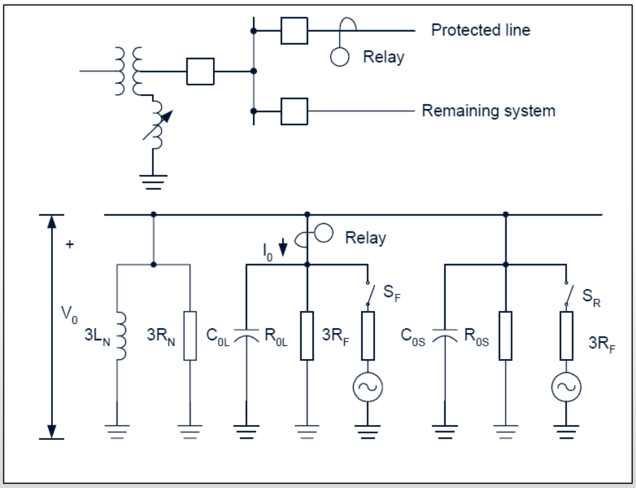
Zero-Sequence Representation



Reverse Fault (close S_R):

$$i_{0L}(t) = \left(C_{0L} \frac{dv_0(t)}{dt} + \frac{v_0(t)}{R_{0L}} \right)$$

$$i_{0L}(t) \cong \left(C_{0L} \frac{dv_0(t)}{dt} \right)$$

Cable Modeling

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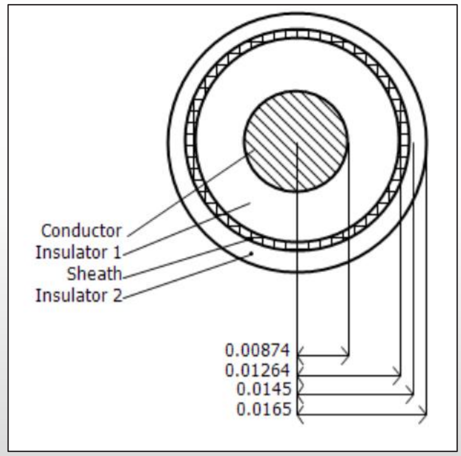
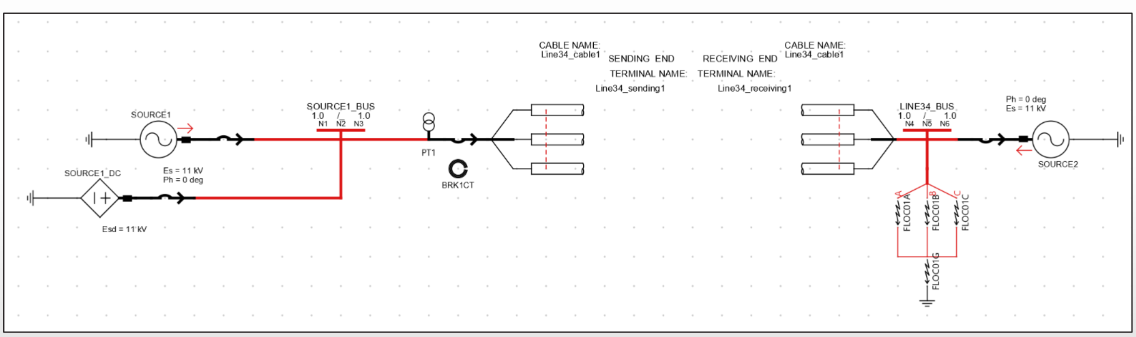
Model Parameters

- Frequency-dependent model
- Defined underground coordinates
- Double insulated layers
- Grounded sheath
- Cable lengths vary from 2 to 10 km



Cable Validation Model



Cable Validation Equations

$$Z_{cable} = \frac{V_1\angle\theta_1 - V_2\angle\theta_2}{I_{12}} = \frac{V_2\angle\theta_2 - V_1\angle\theta_1}{I_{21}}$$

$$R_{cable} = \mathrm{Re}\{Z_{cable}\}$$

$$X_{cable} = \mathrm{Im}\{Z_{cable}\}$$

$$C_{cable} = \frac{I_{V_t} \times T_{V_t}}{V_t}$$

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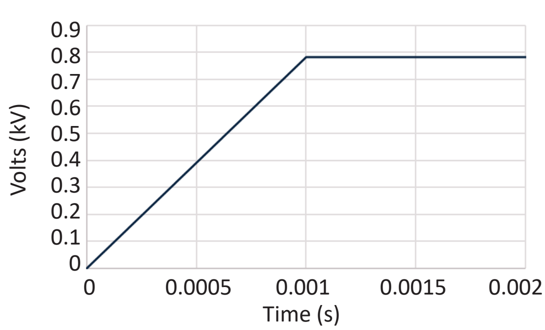
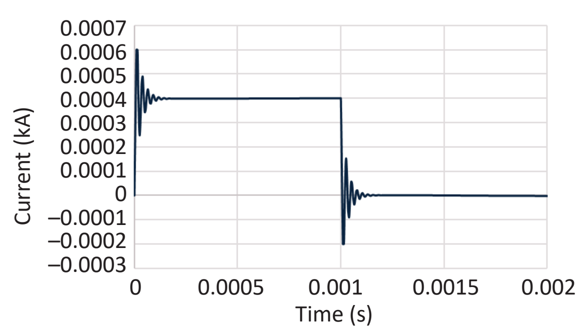
Cable Charging Characteristics





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Cable Validation Results

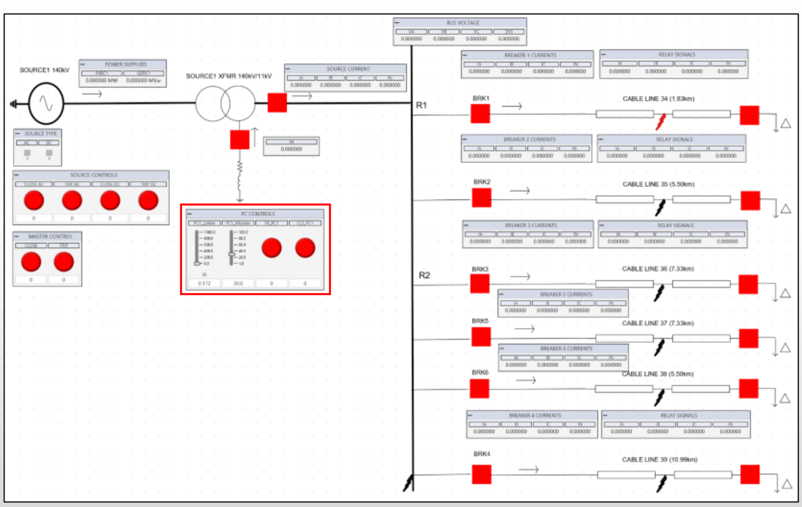
Parameter	Calculated	Expected
Resistance (per km)	0.14 Ω	0.13 Ω
Inductance (per km)	0.28 mH	0.25 mH
Capacitance (per km)	0.51 µF	0.46 µF

Fault Model

Objectives of Fault Model

- Adjust tuning of Petersen coil
- Trigger stable and intermittent faults based on the following:
  - User-defined point on wave of bus voltage
  - User-defined fault location
  - User-defined fault type
  - User-defined fault duration
  - User-defined fault impedance
  - User-defined time between arcs (IGF-type fault only)
  - User-defined arc duration (IGF-type fault only)

Model in RSCAD FX



Petersen Coil Tuning

Determine Tuned Petersen Coil Inductance

1. Determine the total per-phase system capacitive current ($I_{c_{ph}}$)
2. Determine the total per-phase system capacitance

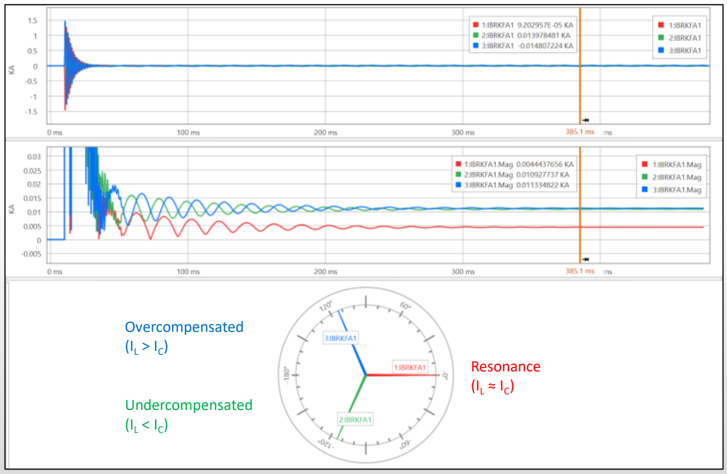
$$C_{sys} = \frac{V_{ph}}{I_{c_{ph}}}$$

3. Determine the per-phase capacitive current during ground fault

$$I_{c_{ph}-fault} = \frac{\sqrt{3} \times V_{ph}}{C_{sys}}$$

4. Determine Petersen coil inductance based on the desired tuning

Fault Current Characteristics



Stable Fault and IGF Logic Model

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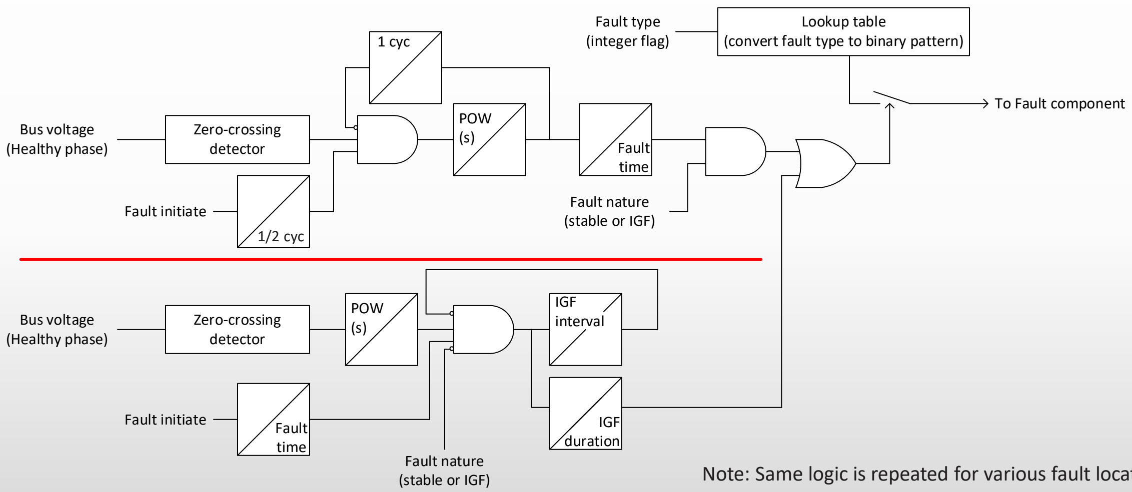
Fault Logic



Note: Same logic is repeated for various fault locations

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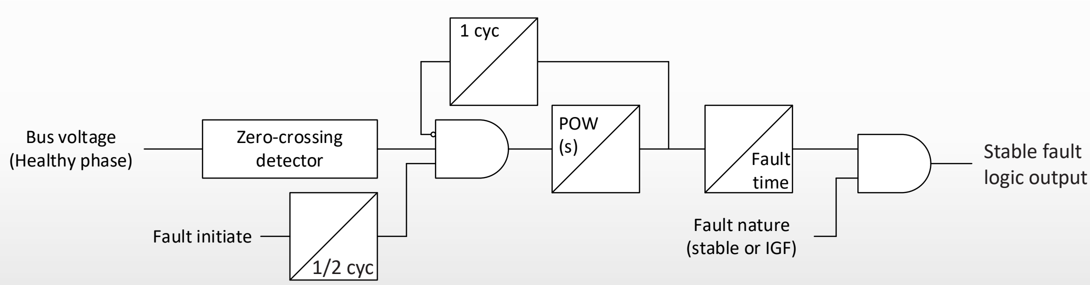
Stable Fault Logic



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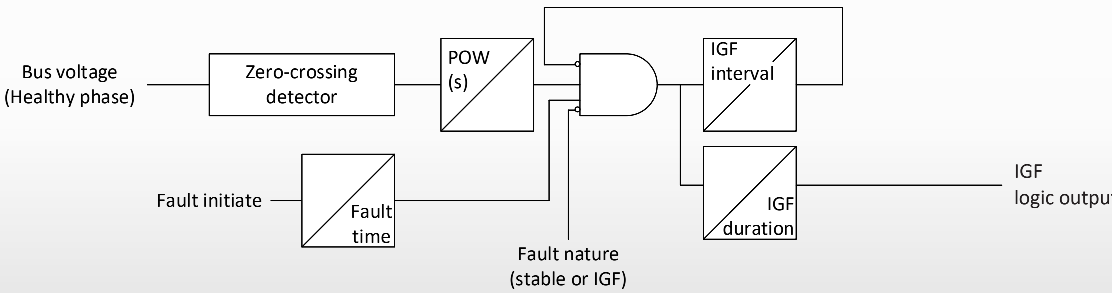
IGF Logic

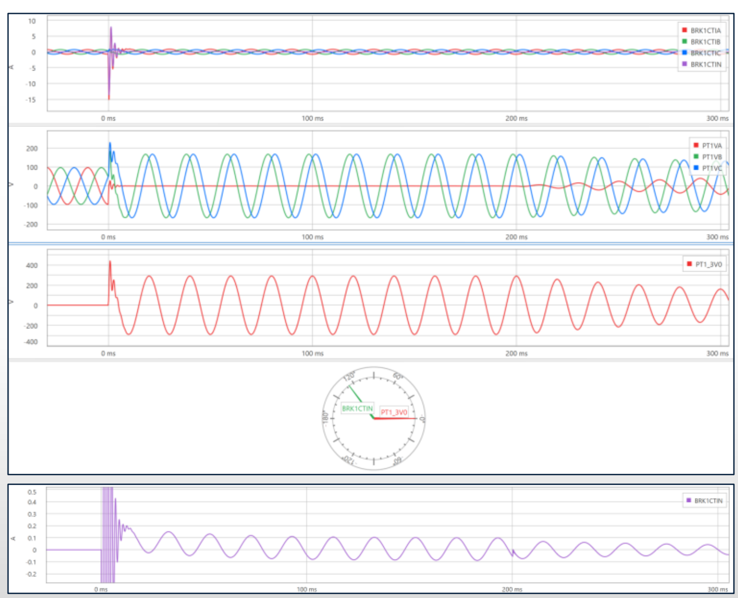


Logic Response: Stable Fault

Fault POW: 90 deg on VA

Faulted Phase: A-phase

Fault duration: 10 cycles (200 ms @ 50 Hz)



Logic Response: IGF

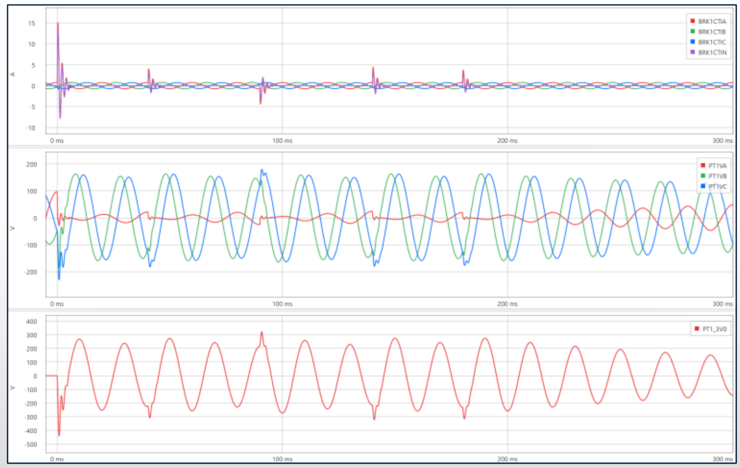
Fault POW: 90 deg on VA

Faulted Phase: A-phase

Fault duration: 10 cycles (200 ms @ 50 Hz)

IGF Interval: 2 cycles (40 ms @ 50 Hz)

IGF duration: 1/4 cycle (5 ms @ 50 Hz)



Python Automation Framework

Fault Automation

1. Read user-defined CSV file that identifies the following:
   - Fault locations
   - Fault types (phase involvement) and nature (stable or IGF)
   - Fault impedances
   - Fault point on wave
   - Arc length and duration (for IGF-type fault)
2. Download event report and event recorder data from relay
3. Save relay response obtained through GOOSE protocol in CSV file

Customized Functions

RTDS functions:

button_pulse(button_name)
slider_setval(slider_name, slider_value)
dial_setval(dial_name,dial_value)

Relay functions:

relay_connect(relay_address)
relay_ser(relay_object)
relay_clear_ser(relay_object)
relay_setting(relay_object, setting_str,setting_value)

Python Execution Example

```
  import telnetlib
Relay is Enabled
RSCAD FX is not connected.
establishing connection to 127.0.0.1:53738
Forcing connection to user-defined rack
LAUNCHING MODEL IN RSCAD FX
Case opened.                                        [####################] 100.00%
The RSCADFX compile completed successfully.         [####################] 100.00%

SENDING RELAY SETTINGS
INITIALIZING MODEL WITH USER SETTINGS

Created directory to save events

SETTING CT BURDEN

RUNNING MODEL

Case started.                                       [####################] 100.00%
                                                    [##########..........] 50.00%
SETTING FAULT POW
SETTING LINE ANGLE
RUNNING TEST CASE:  | POW = 0.0deg | X/R = 100.0
CLOSING ALL LOAD BREAKERS
SETTING FAULT TYPE
RESETTING CT 1 FLUX
RESETTING CT 2 FLUX
RESETTING TRIP TIMER
TRIGGERING FAULT

TRIP OCCURRED

Event downloaded
```

Questions?

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