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GU304: Effective Grounding for IBRs: Challenges, Solutions & Advanced Modeling



Orange & Rockland
Rockland Electric Company

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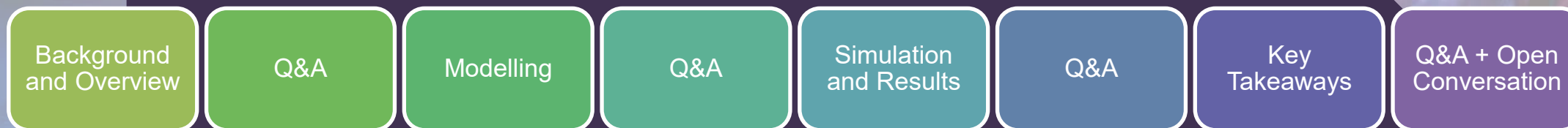
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Effective Grounding for IBRs: Challenges, Solutions & Advanced Modeling





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Orange & Rockland Utilities (O&R) is a regulated electric and gas utility serving customers across southeastern New York and northern New Jersey and is the subsidiary of Con Edison.

Haowei Lu is a Senior Engineer at O&R with experience of all types of power system study —especially around system reliability, protection coordination and DER interconnections.

He earned his Ph.D. from New York University (NYU) and brings a strong analytical background to modern grid challenges, including topics of DER integration, Dynamic rating, FEM analysis and system reliability.



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K&A Engineering Consulting, P.C. ("K&A") is a privately held, nationally certified Minority Business Enterprise (MBE) providing comprehensive consulting, engineering and design, program/project management, construction management, and support services to utility and industrial clients

Abinash Chaudhary acts as Principal Engineer for Power System Studies & Planning department within K&A. He is deeply involved in T&D planning and EMT studies for various utility and developer clients across the states.

Having earned his Master's in Electrical Engineering with a specialization in Power Systems, Abinash is deeply involved in continuous research, innovation, and R&D efforts at K&A, as well as within the open-source community.

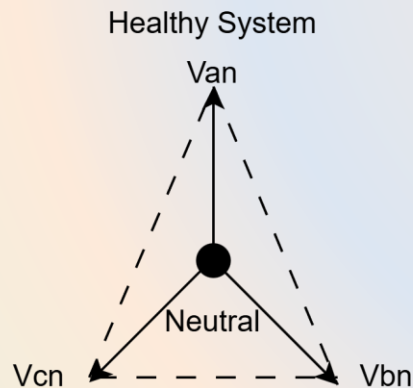
Effective Grounding

An effectively grounded system is one that is grounded through a sufficiently low impedance (inherent or intentionally added, or both) so that the COG does not exceed 80%.

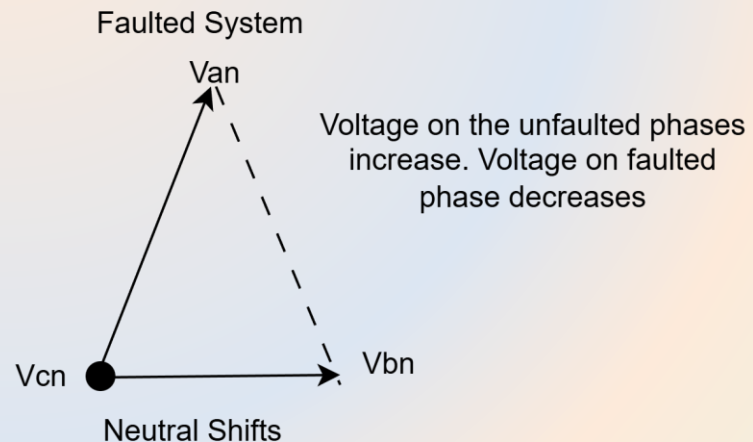
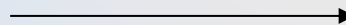
Effective grounding is not optional — it is a critical requirement for ensuring safety, system stability, and equipment protection in any electrical power system.

Limit ground-fault current and ensure proper fault clearing

Effective grounding provides a low-impedance path, so protective devices operate correctly and quickly during ground faults.



Faulted on one phase,
Generation is islanded



Quantifying Effective Grounding: CoG and GFOV

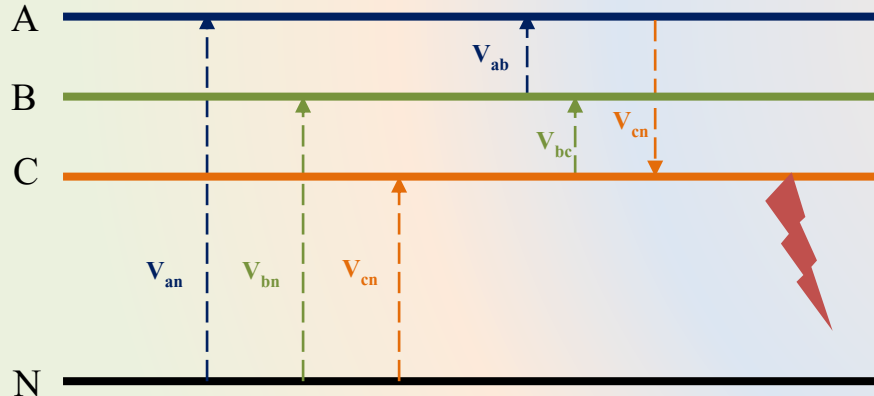
IEEE C62.92.1 defines the Coefficient of Grounding (CoG):

Coefficient of Grounding (COG) is a measure of how high the line-to-ground voltage on a healthy (unfaulted) phase becomes during a ground fault, compared to the normal line-to-line voltage under unfaulted conditions.

$$CoG = \frac{V_{LG}}{V_{LL}} \times 100\%$$

V_{LG} : Line to Ground voltage on unfaulted phase

V_{LL} : normal line to line voltage under unfaulted conditions



$$CoG_a = \frac{V_{an}}{V_{ab}} \times 100\%$$

$$CoG_b = \frac{V_{bn}}{V_{ab}} \times 100\%$$

Positive-sequence voltage:

$$V_1 = V_{1,prefault} - I_1 Z_1$$

Negative-sequence voltage:

$$V_2 = -I_2 Z_2$$

Zero-sequence voltage:

$$V_0 = -(V_1 + V_2)$$

Unfaulted phase B Voltage

$$V_b = V_0 + a^2 V_1 + a V_2$$

Faulted phase A current

$$I_{fault} = \frac{V_{1,prefault}}{Z_0 + Z_1 + Z_2}$$

For typical synchronous generator dominated system:

$$Z_1 = Z_2, Z_0 = kZ_1$$

After apply it to the SLG condition when ,

$$CoG = \frac{V_{LG}}{V_{LL}} \times 100\% = f(k)$$



CoG Continued: the famous ratio

$$X_0/X_1 \leq 3 \text{ and } R_0/X_1 < 1$$

The values “3” and “1” are a conservative rectangular bound on previous “k” that was found (empirically + analytically) to keep CoG below 0.8 for conventional systems dominated by rotating-machine sources (where the assumptions $Z_1 \approx Z_2$, $Z_0 = kZ_1$ & $R_1 < X_1$)

$X_0/X_1 \leq 3$ controls overvoltage

- Zero-sequence reactance must not exceed positive-sequence reactance by more than 3 times
- Prevents unfaulted phases from exceeding safe overvoltage limits during SLG faults.

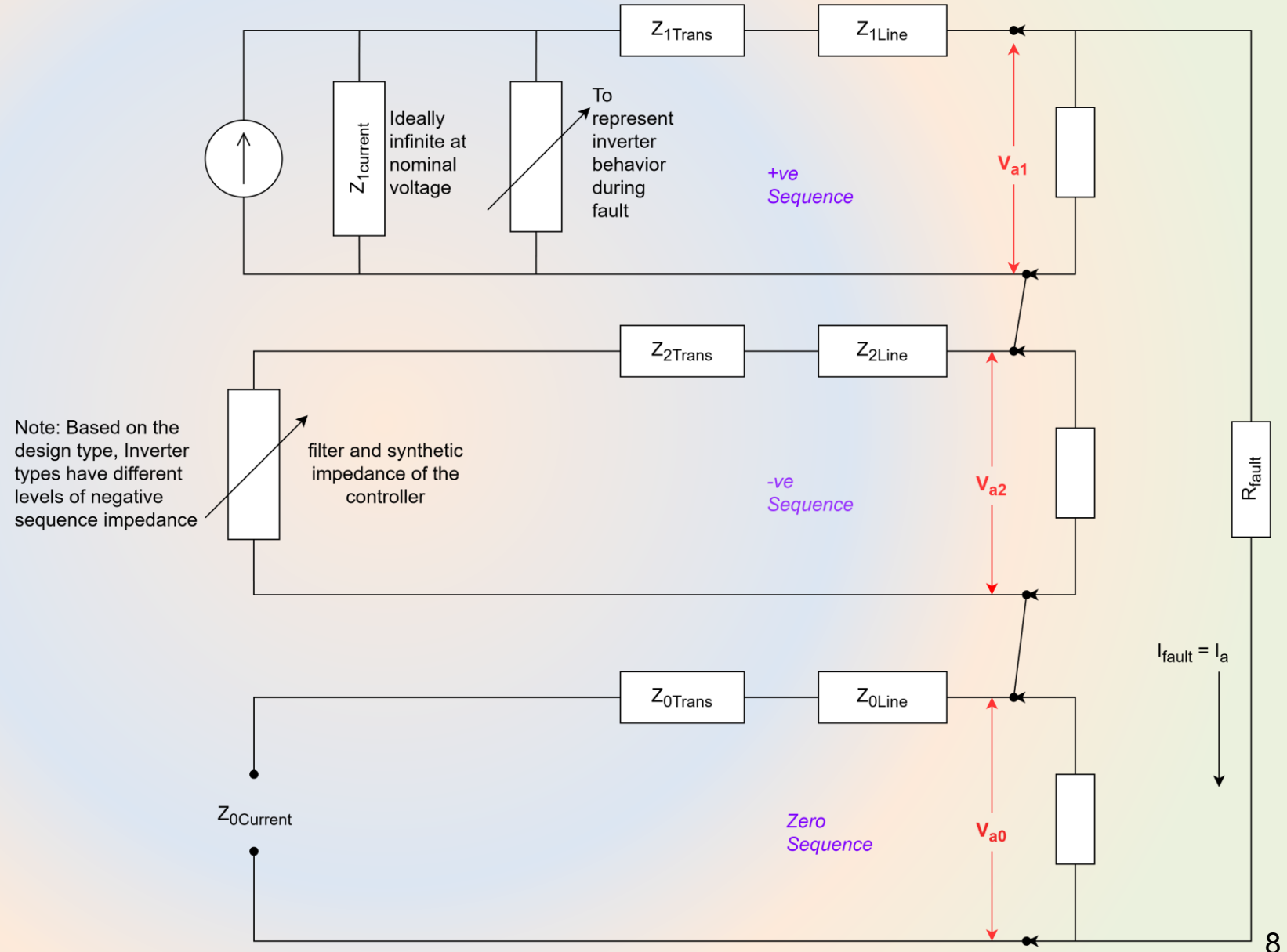
$R_0/X_1 < 1$ controls arcing + fault current

- Zero-sequence resistance (neutral grounding resistance) must be limited
- Keeps SLG fault current high enough to let protection device to clear faults
- Prevents arcing ground, restrikes, and transient overvoltage.

Sequence Diagram for SLG fault with IBR

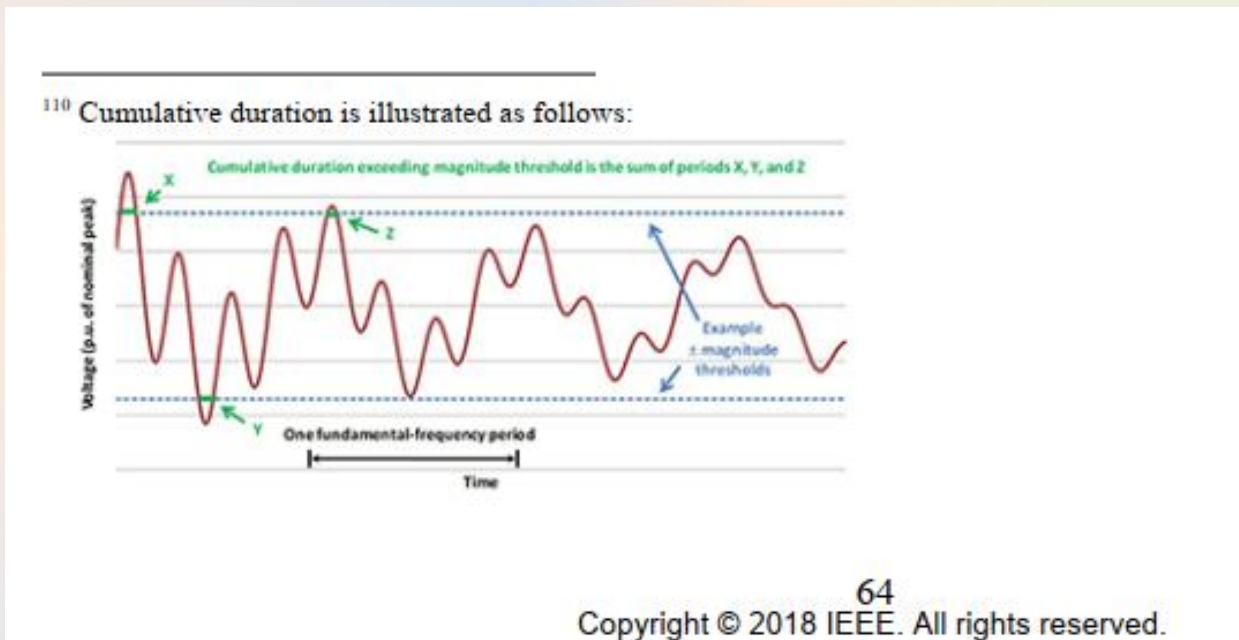
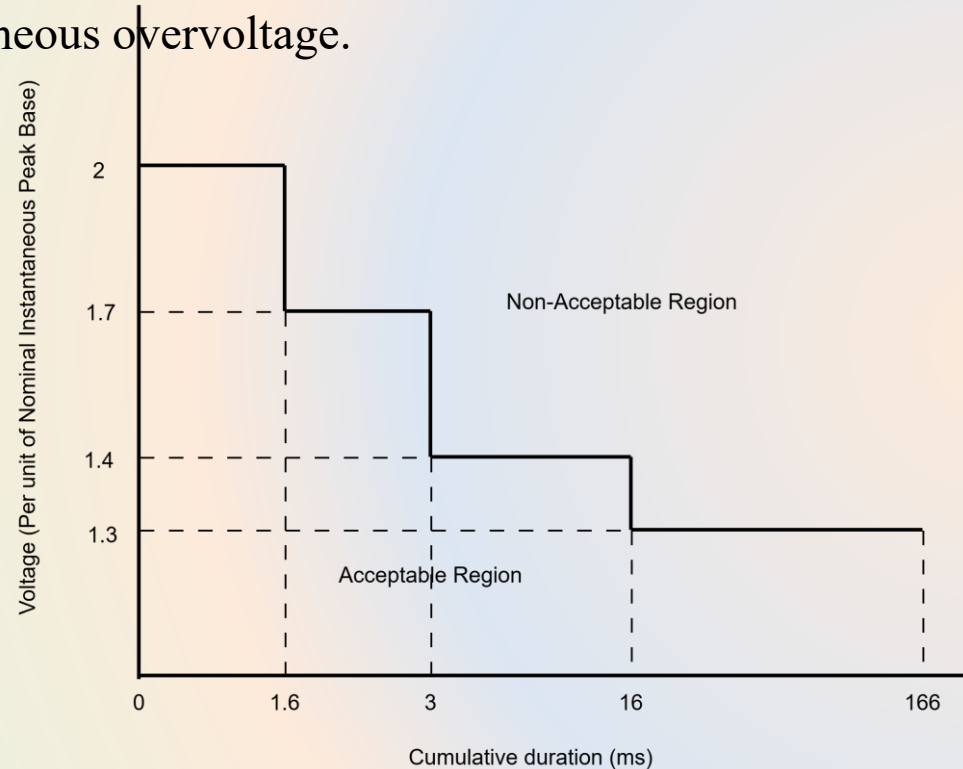
Inverter based-DER is a **current - regulated source**.

$Z_1 \rightarrow$ large
 Z_2 variable
 $Z_0 \sim$ open,



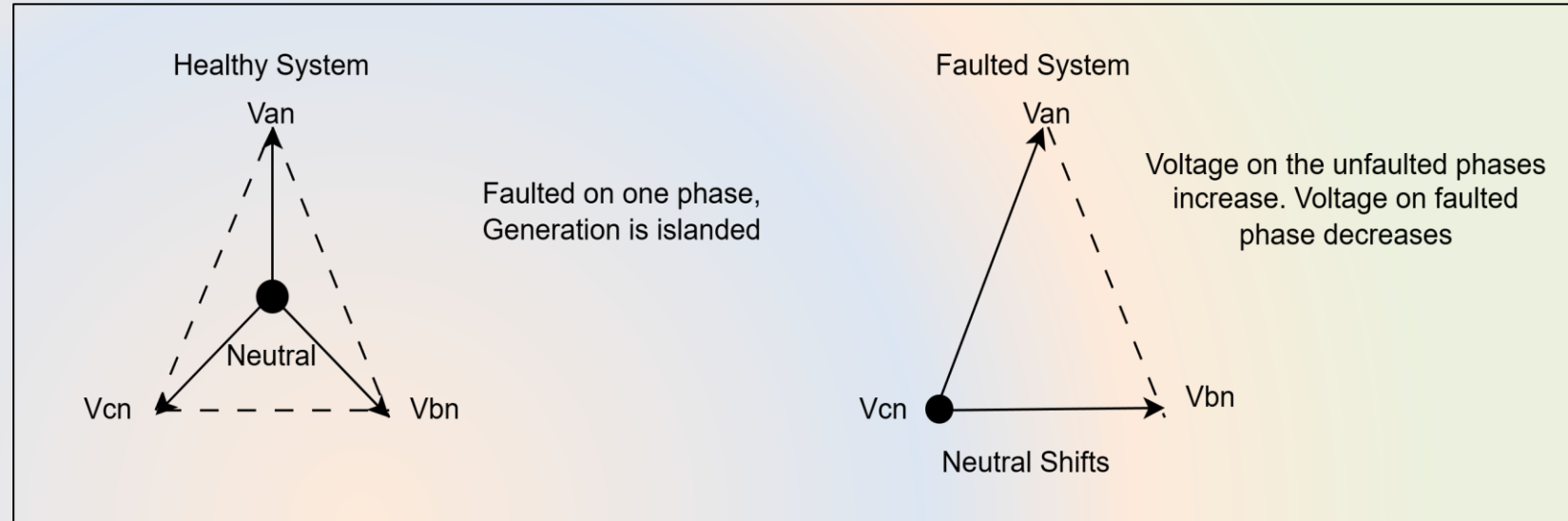
IEEE Requirements for TOV

Figure below shows the IEEE 1547 – 2018, Section 7.4.2, Page 64, Figure 3 power quality limitation of the instantaneous overvoltage.

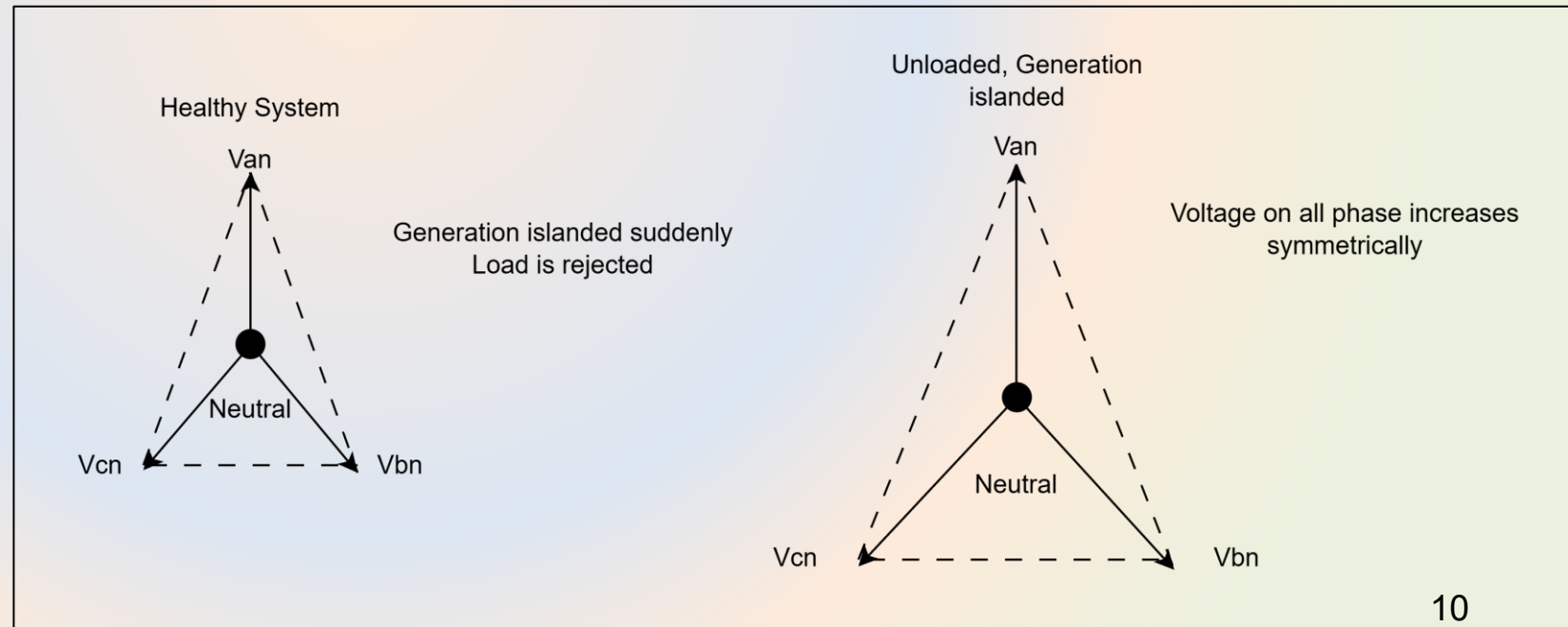


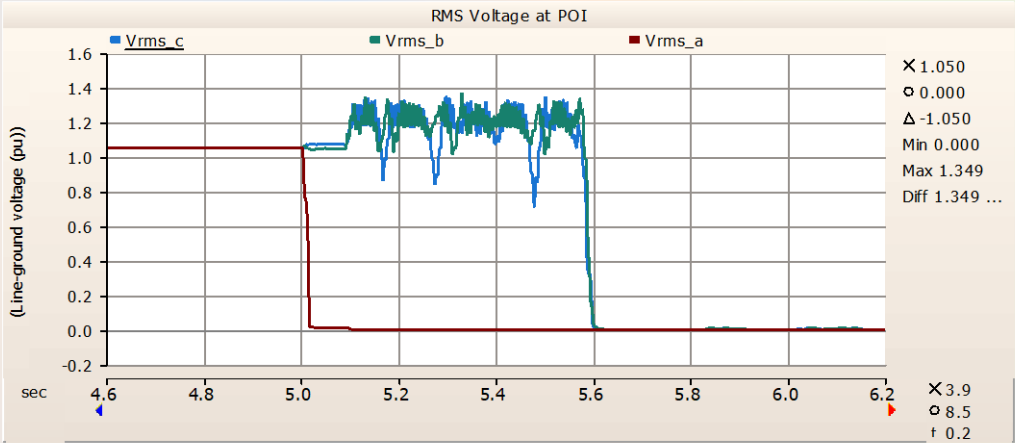
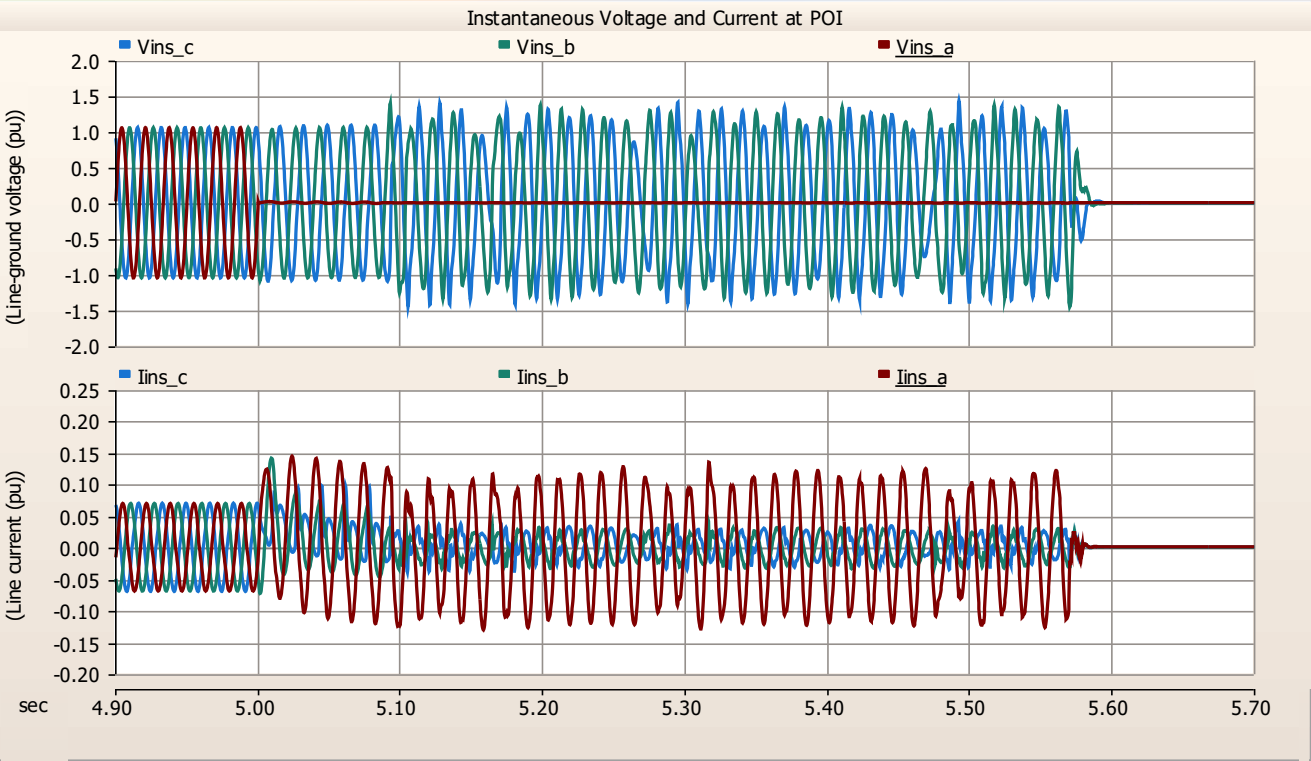
IEEE Standard transient overvoltage limits.

Ground Fault Overvoltage (GFOV)—When a single phase to ground fault happens and the ground source is lost; the un-faulted phases can reach dangerous overvoltage due to the “neutral shift” phenomena.

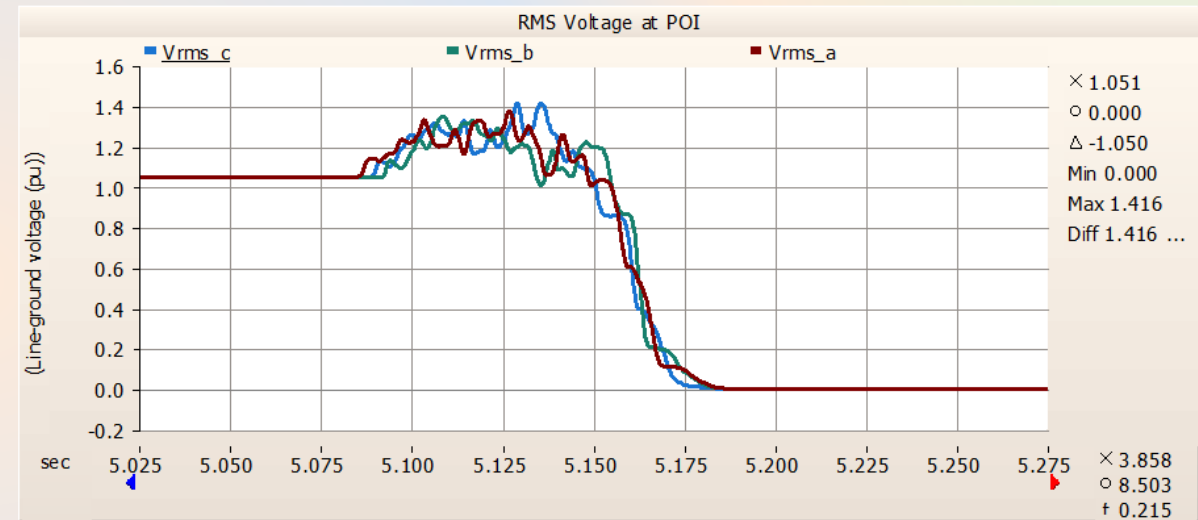
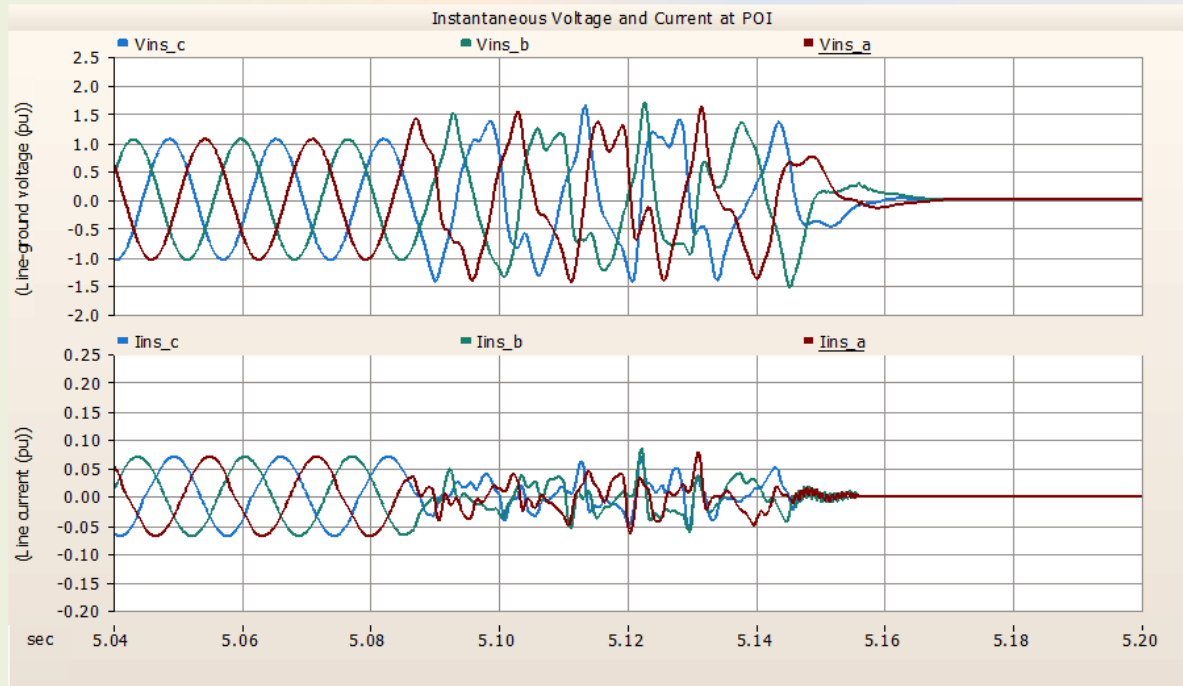


Load Rejection Overvoltage (LROV) —When an upstream protection device opens forming an island with DERs, the voltages in the island can surge during the first moments of the island.





GFOV is related to the grounding configuration and condition



LROV is not depended on grounding, but on the Generation to Load ratio.

O&R practice of performing effective grounding evaluation for DER

Challenges

- 1.High DER Penetration: More complex interactions with grid from reverse power flow.
- 2.DER Grounding Criteria: Differ from synchronous machine, inverter grounding review requires EMT study to get the Voltage during the fault.
- 3.System Transient Events: Fast transient phenomena occurred.
- 4.Rapid Technology Development: Modern inverters have advanced functionalities that need thorough reviews.

O&R Tech Engineering

- 1.O&R issued the EMT requirements and guidelines in Sep 2023.
- 2.EMT study required for: Project > 500 kW & Aggregate Feeder DER/Min Load ratio >100%.
- 3.Currently >20 large DER projects successfully completed the full EMT studies.

Study Scope

- 1.Evaluate Ground Fault Detection to meet reduction of reach, fault contribution protection per NYSIR in software Aspen.
- 2.Evaluate Transient Overvoltage Compliance with Standards: Ensuring DERs comply with IEEE Std 1547-2018 with EMT screen, ISGT tools or PSCAD.

Screen 16	Protection	Overvoltage - Distribution System Fault	IEEE 1547-2018 TOV Limit	
Screen 17	Protection	Effective Grounding	IEEE C62.92.6 Coefficient of Grounding <0.8	

What O&R has tried to help a project to avoid EMT Study

EMT Studies Are Time-Consuming

- A separate EMT feeder model must be created; it cannot reuse the existing steady-state CYME feeder model.
- Requires contacting the DER developer and, often, frequent communication with the inverter manufacturer.
- Must obtain commercial PSCAD models, library files, and guidance on where to adjust inverter settings.
- EMT simulations must be set up, executed, and validated by Engineer with specialized expertise.

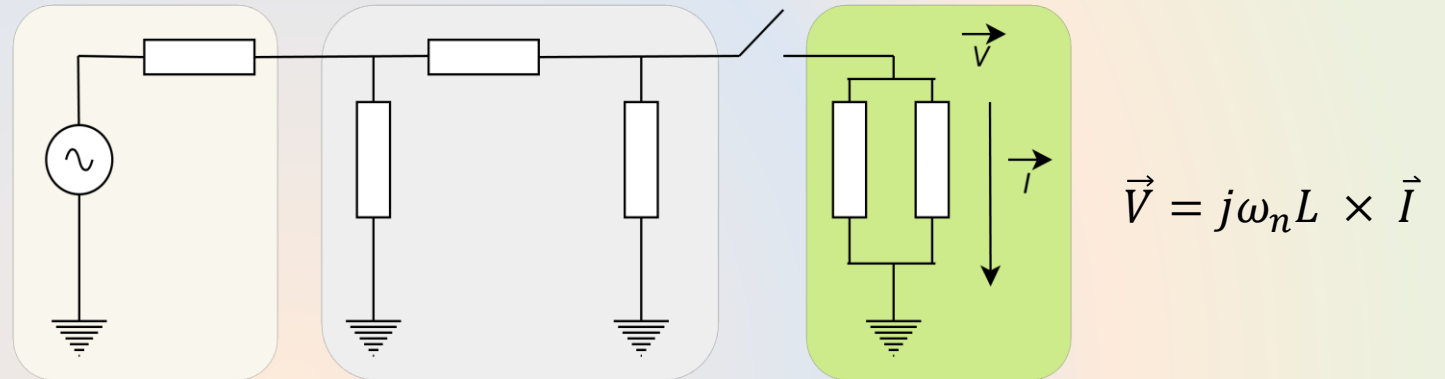
EMT Studies Are Costly

The overall workload—model building, vendor coordination, data acquisition, and simulation time—increases both labor and project cost.

RMS vs EMT

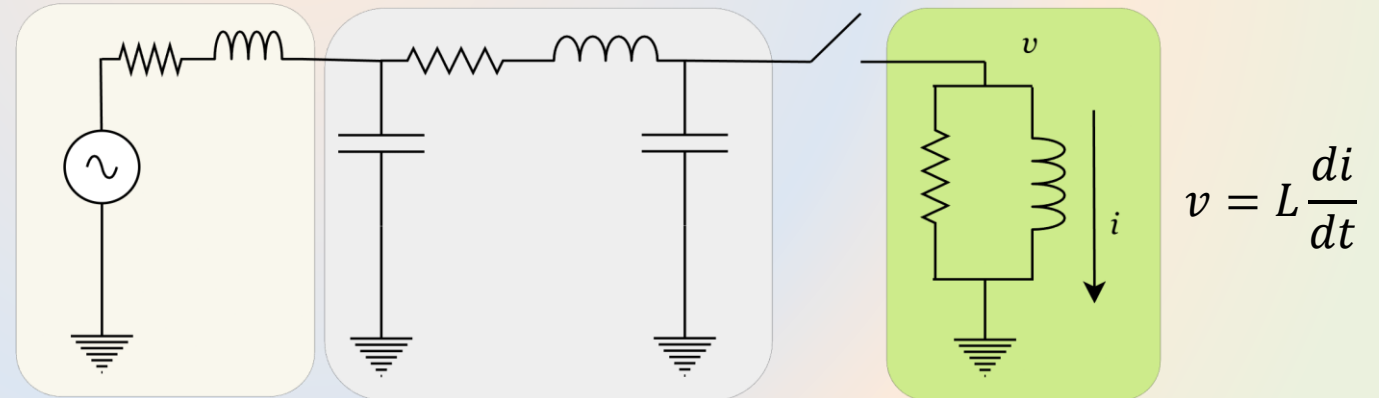
RMS Simulation Model (Phasor Domain)

0.1s~Hour, Day, Month, Year

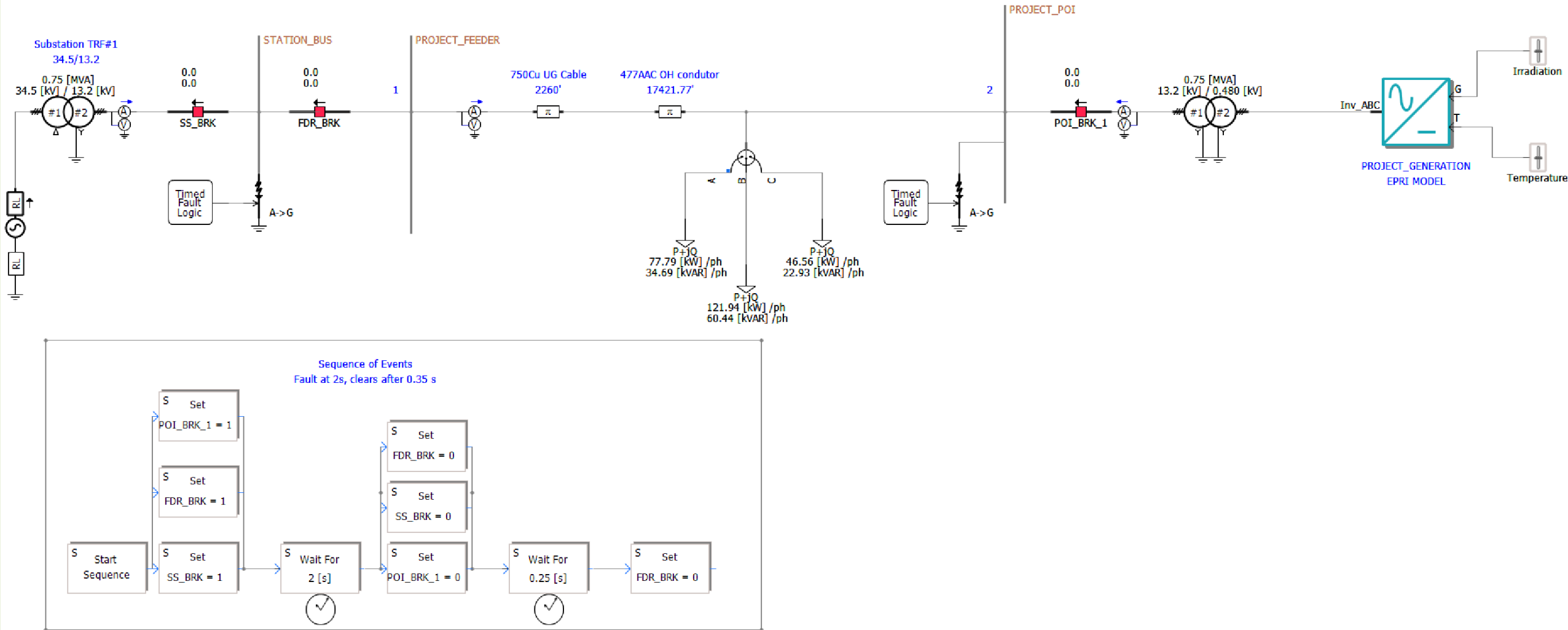


EMT Simulation Model (Time Domain)

$10^{-5} \sim 0.1$ s

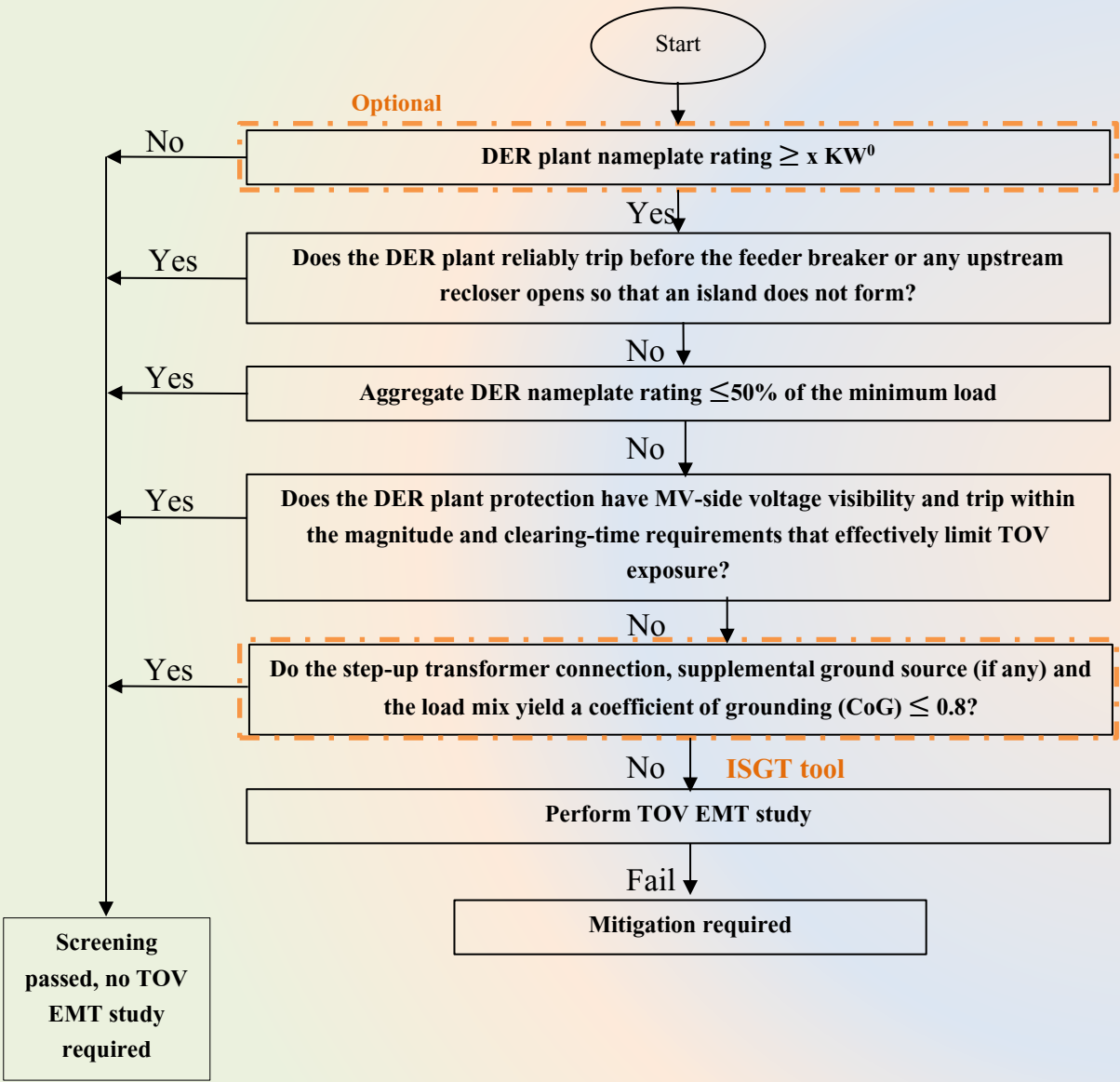


Required DER EMT Model Components for Study

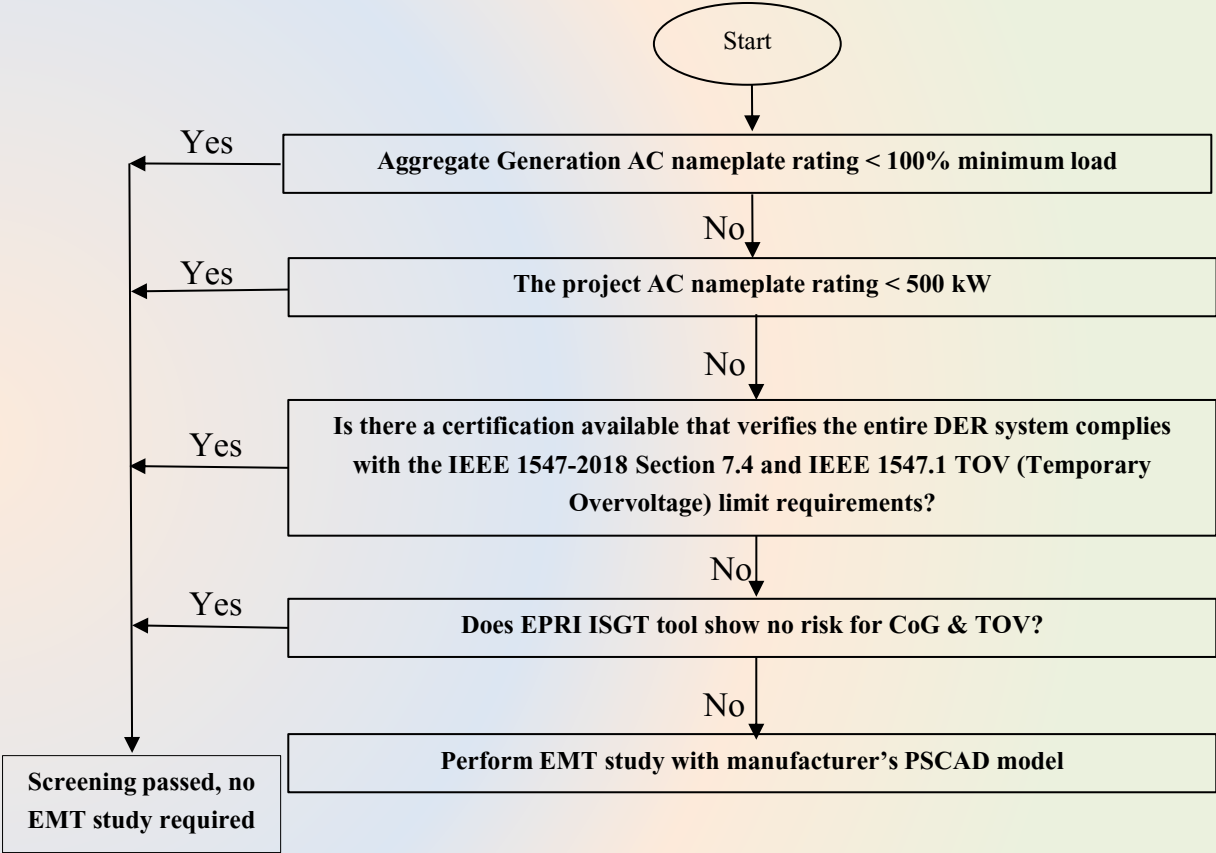


Inverter negative-sequence impedance is largely an unknown value. It can be between 0.1p.u. and infinity with any impedance angle, depending on the inverter control algorithms.

EPRI EMT screens



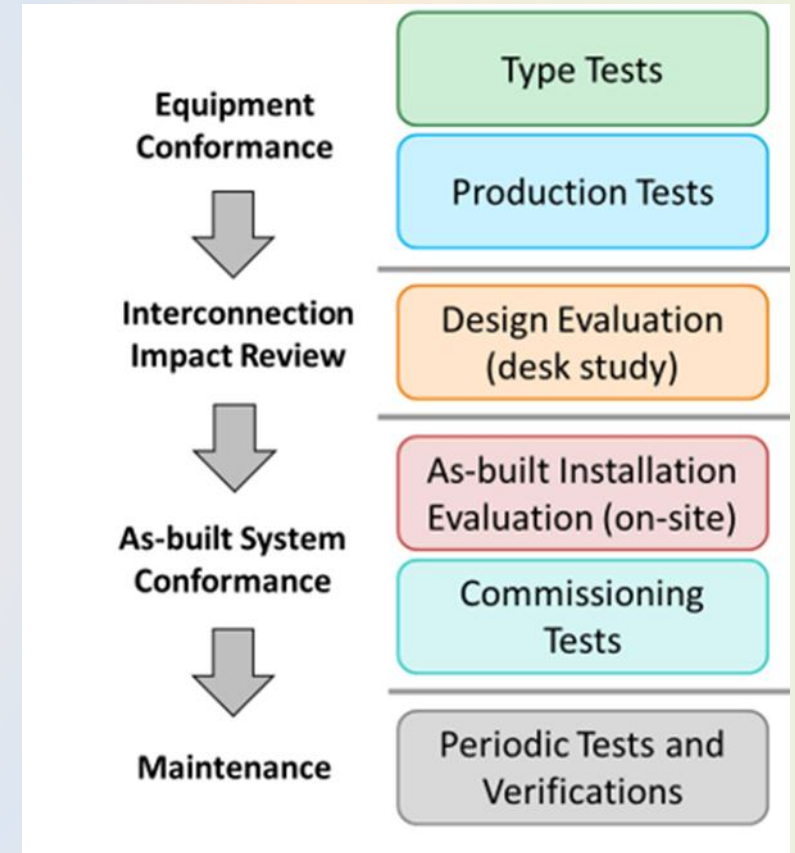
O&R EMT screens



1547.1--Does a UL1741SB compliant inverter mitigate the risk of TOV?

IEEE 1547.1 — Conformance Tests for DER Interconnection

- **Purpose**
 - Companion to IEEE 1547: provides official test procedures to verify that DER (solar, storage, inverters, etc.) meet IEEE 1547 performance, safety, and interoperability requirements.
- **Type Tests (Clause 5) — Key Items**
 - Overvoltage Trip Test (5.4.2): Verify the EUT trips within required clearing times when voltage exceeds thresholds; confirm adjustable trip settings span the ranges required by IEEE 1547.
 - Limitation of Overvoltage Contribution (5.17):
 - Load Rejection Overvoltage (LRO) test (5.17.2): With sudden load disconnection, the EUT's voltage response must remain within voltage-duration limits per IEEE 1547-2018 Figures 3 & 13.
- **Core Compliance Criterion (Overvoltage Limits)**
 - “The cumulative duration for respective voltage levels shall not exceed the limits of Figure 13 in IEEE Std 1547-2018.”
 - EUT must stay at or below both: (1) peak voltage magnitude and (2) cumulative duration envelopes.
 - MRA does not apply to this determination. (the 150% measurement accuracy of the EUT)
- **EUT (Equipment Under Test):**
 - the specific DER unit, inverter, controller, protection device, or DER system undergoing IEEE 1547.1 tests.



840 kW Solar DER

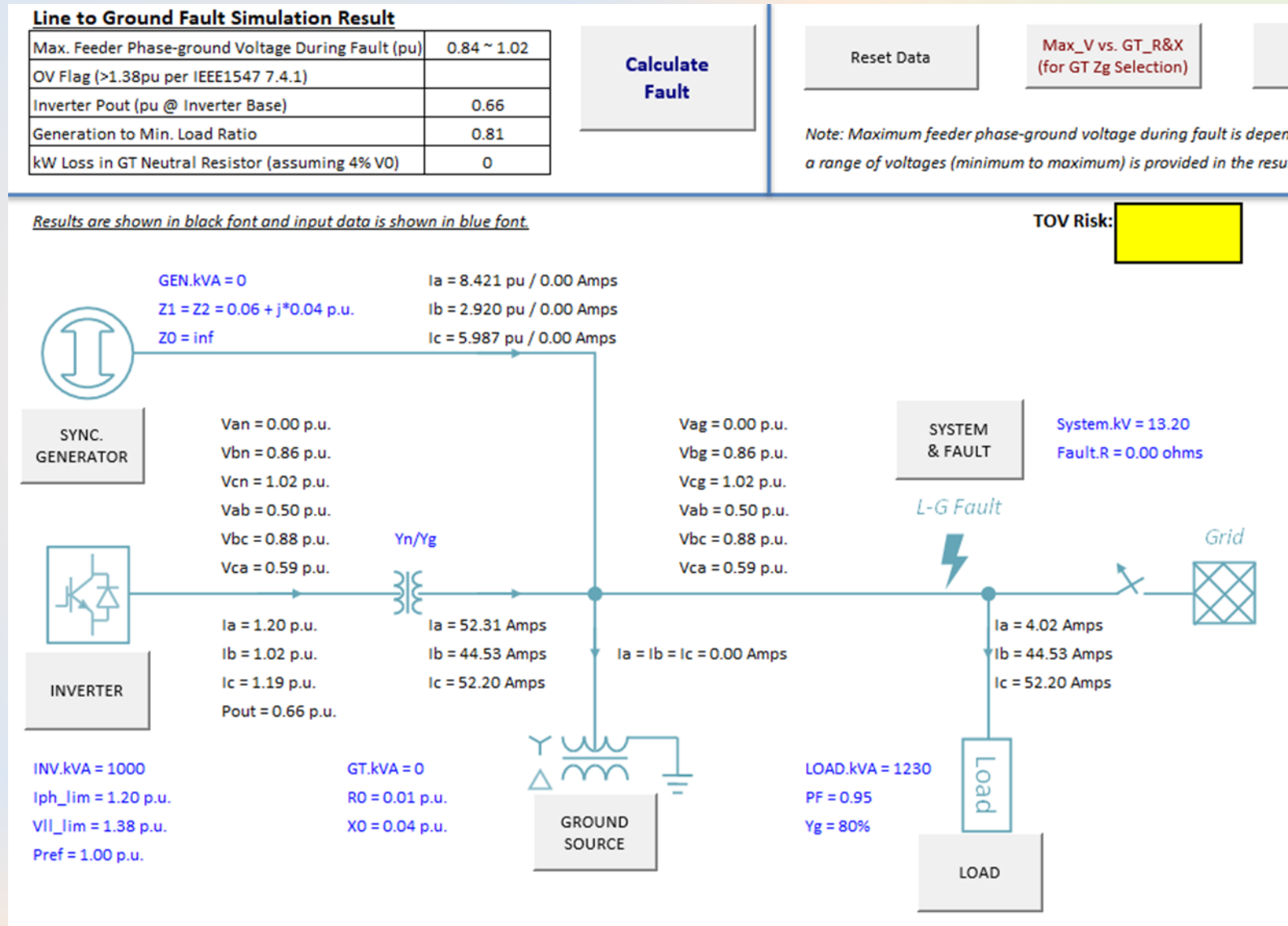
ISGT tool works well for

- project that slightly > 500 kW
- Aggregated DER/Feeder min load is close to 100%

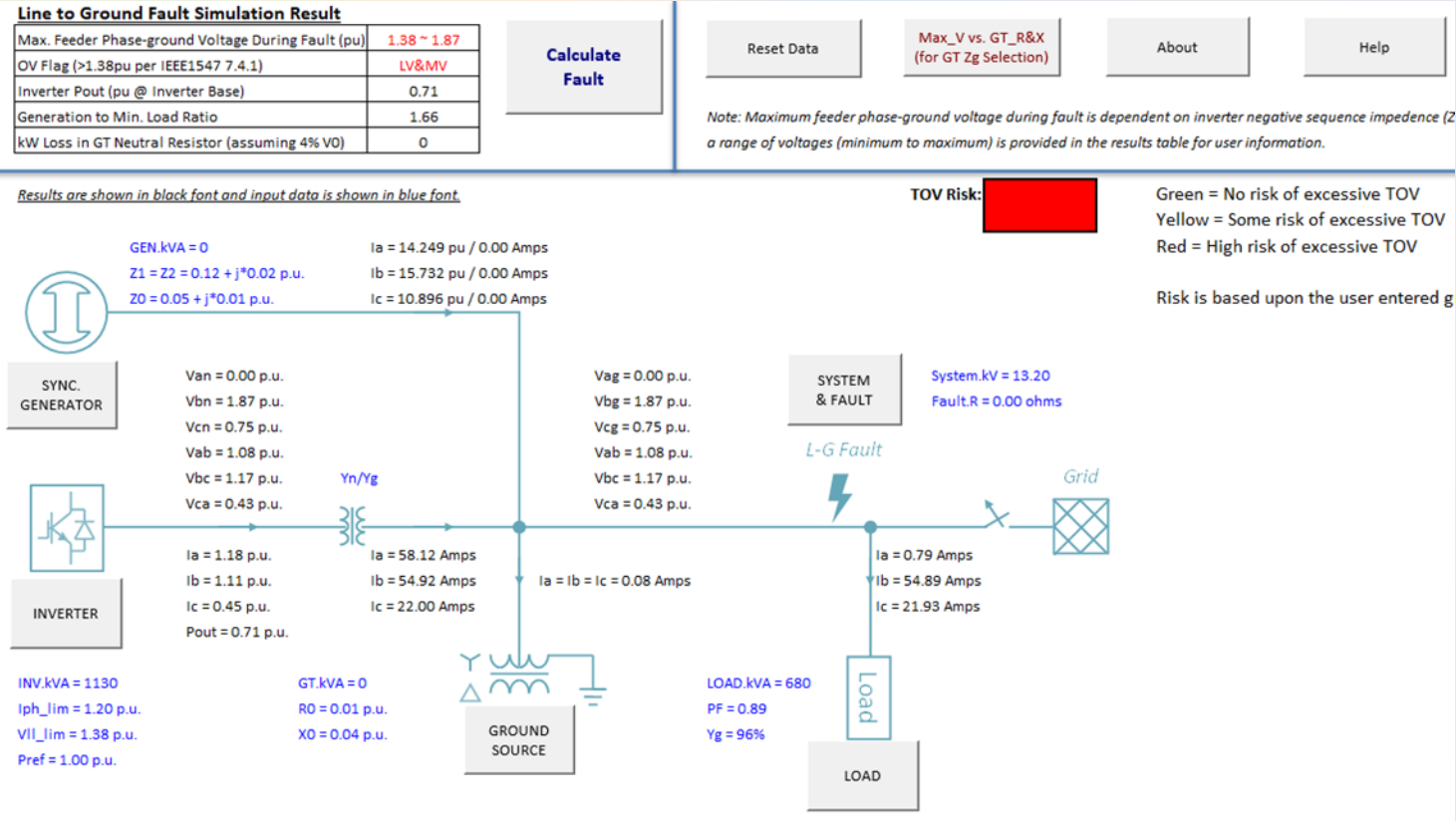
ISGT shows max TOV is 1.02 p.u,

COG is 0.59

No PSCAD study required



760 kW Solar DER



ISGT shows max TOV is 1.87 p.u.

<https://www.epri.com/research/products/000000003002028194>

System Condition: under islanding scenario in minimum load condition with steady state upgrades included.

Ground Fault Over Voltage (GFOV) Analysis

- Apply Single Line Ground fault at project's POI on one of the phases. We select the phase with highest DG/load ratio.
- Open the feeder breaker and/or substation breaker after 5 cycles.
- Measure voltage at the project's POI once the island is formed.
- Continue recording voltage until the project trips.
 - If the voltage is not within IEEE 1547-2018 standard section 7.4.2 then there are TOV violations and require mitigation.
 - Add CoG results

Load Rejection Over Voltage (LROV) Analysis

- Open feeder breaker and/or substation breaker.
- Measure voltage at the project's POI once the island is formed.
- Continue recording voltage until the project trips.
- If the voltage is not within IEEE 1547-2018 standard section 7.4.2 then there are TOV violations and require mitigation.

RECAP – RMS is not enough.

Cycle-Averaged Modeling: Averages electrical waveforms over an entire cycle rather than tracking instantaneous points.

System-Wide Efficiency: Delivers faster results and broad insights into voltage, current, and power flows.

Low Resolution: Provides a simplified data view that lacks granular detail.

Assumes Sinusoidal Balance: Operates on the premise of balanced, steady-state conditions.

Fundamental Frequency Focus: Ignores higher frequencies and sub-cycle transients.

Limited Fault Analysis: Less effective at capturing the complexities of asymmetrical faults.

RECAP – EMT simulation

High-Resolution Waveforms: Resolves actual waveforms at micro- to millisecond intervals, rather than assuming sinusoidal balance.

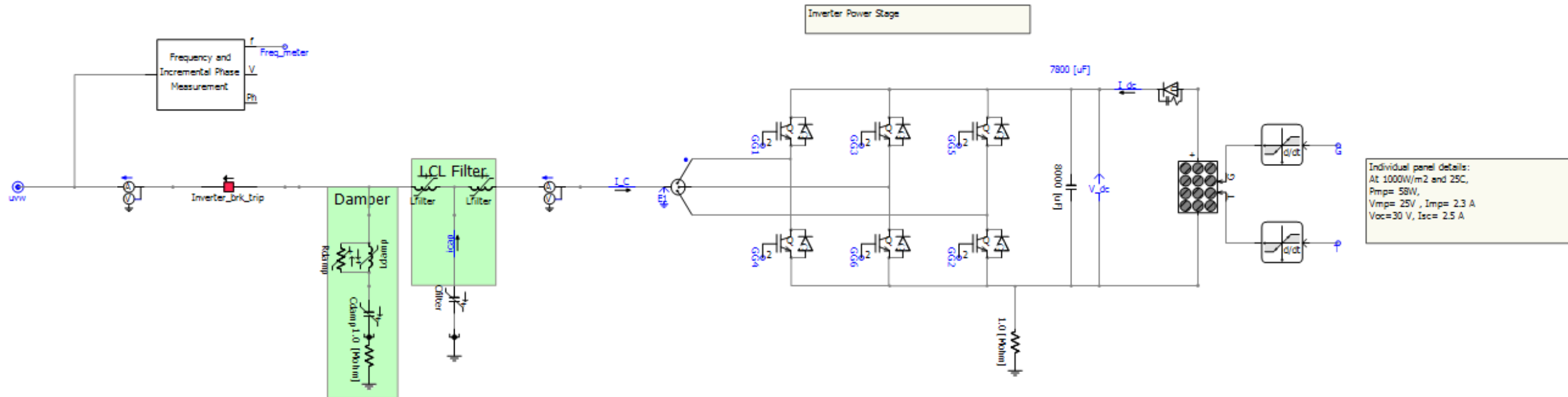
Granular Event Tracking: Reveals sub-cycle harmonics and specific converter switching events.

Dynamic Control Behavior: Captures detailed protection interactions and converter Phase-Locked Loop (PLL) behavior.

Complex Fault Analysis: Accurately models asymmetrical faults.

Frequency Analysis: Identifies high-frequency resonance issues that simpler models might miss.

EMT is important for IBRs



- Inverters use fast-switching power electronic devices (IGBTs, MOSFETs, SiC) that operate beyond RMS time resolution.
- Inverter switching produces high-order and non-integer harmonics that can stress filters, transformers, and protection systems.
- EMT simulation captures detailed control and protection actions such as current limiting, gate blocking, and fault ride-through.
- Inverter protection firmware can respond to faults within a few milliseconds, requiring sub-cycle electromagnetic transient modeling.

Blue Cut Fire



A major system disturbance occurred in Southern California on August 16, 2016.

During the disturbance, inverters detected the fault and approximately 1,200 MW of solar generation disconnected, creating a significant generation shortfall.

Inverters that relied on near-instantaneous frequency measurements experienced erroneous tripping due to transient and distorted waveforms caused by the fault.

Adding a short time delay to frequency-based tripping allows inverters to ride through transient disturbances without disconnecting.

Most installed inverters are configured to momentarily cease current injection for voltages above 1.1 pu or below 0.9 pu. Some inverters returned to pre-disturbance output at slow ramp rates after momentary cessation, prolonging the generation deficit.

Configuring inverters to restore output within five seconds or less after voltage recovery reduces system impact.

When to use RMS?

Long-term planning

Seasonal or hourly simulations

Evaluate multiple design options

Optimization Studies

Transmission and Distribution planning studies dependent on existing databases

How to obtain EMT from RMS?

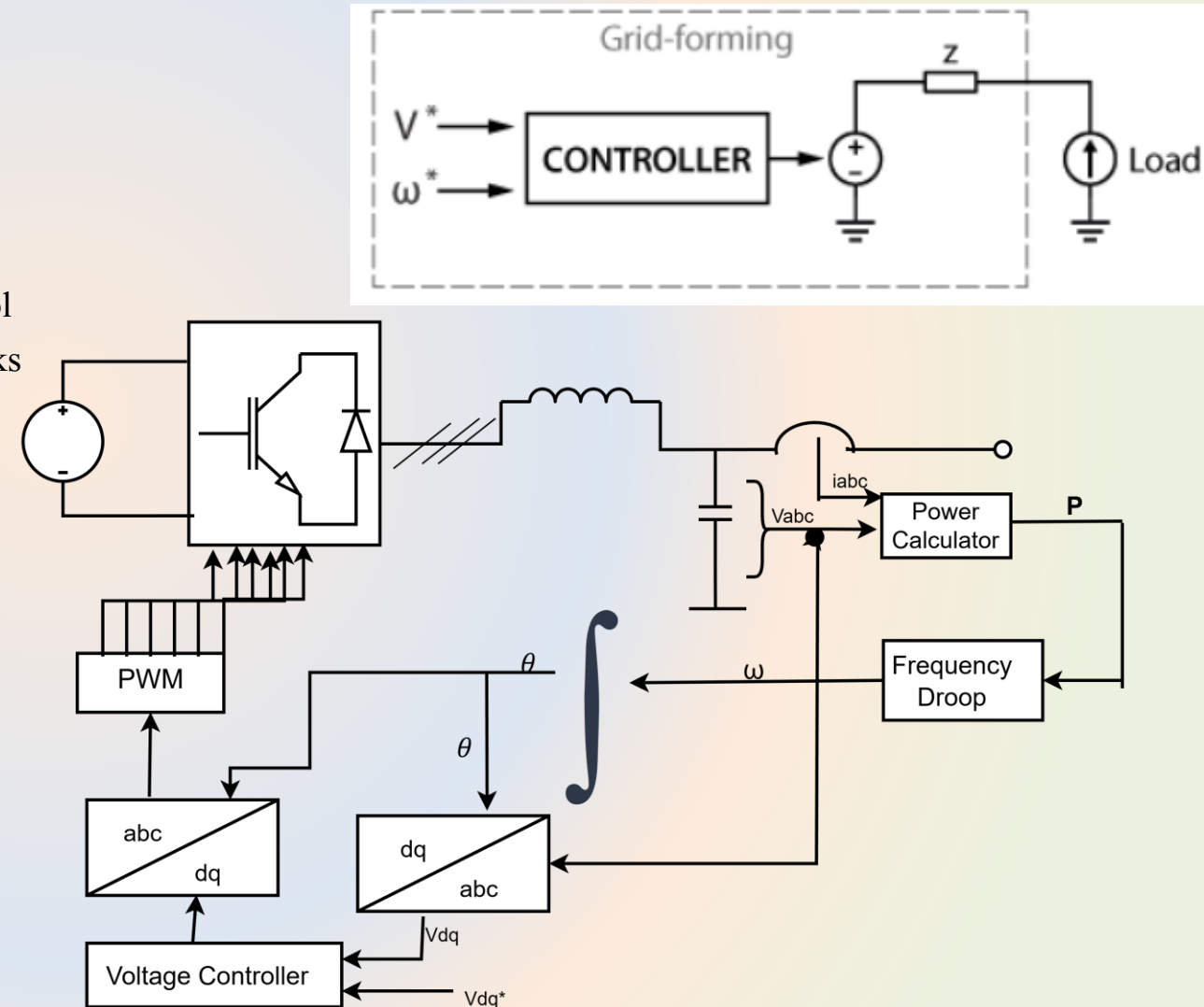
Steady state models are easy to build. You can just import from the GIS. Hence, RMS models are readily available.

To model the EMT model from RMS, we need following info:

- a. Source impedance and type
- b. OH conductor information
- c. UG conductor information
- d. Transformer information
- e. Regulating device information
- f. Capacitor information
- g. Generation information
- h. Blackbox models
- i. Loads
- j. Protective device and its sequence of operation

Grid-Forming Inverters (GFM)

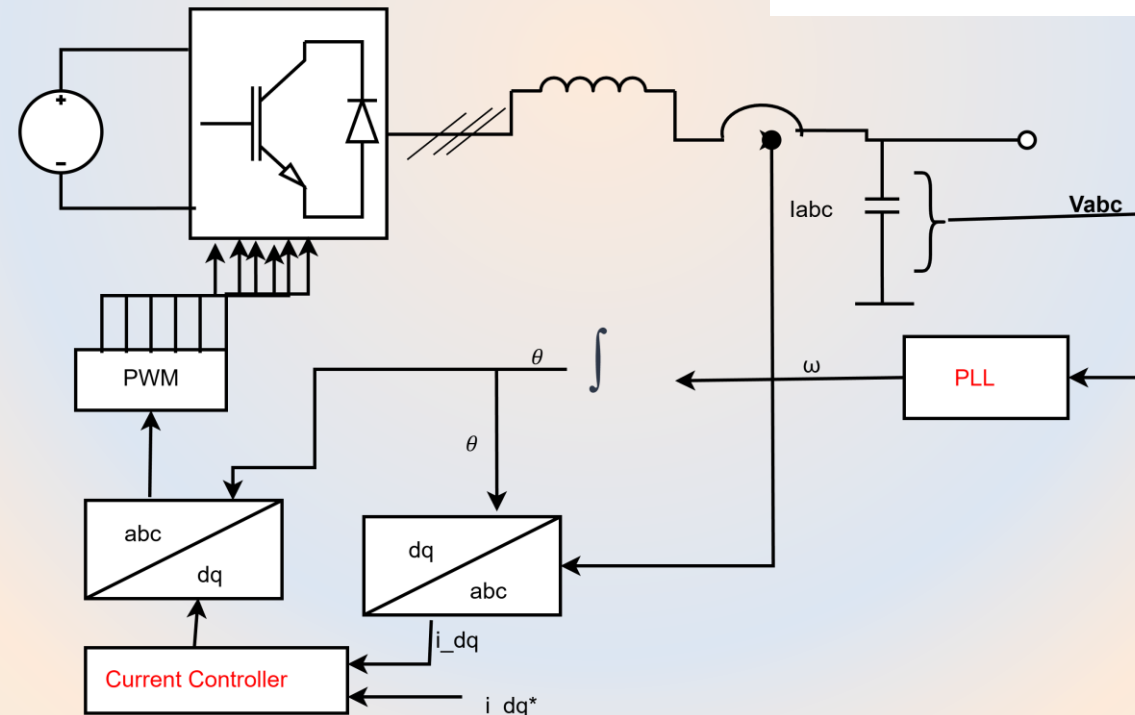
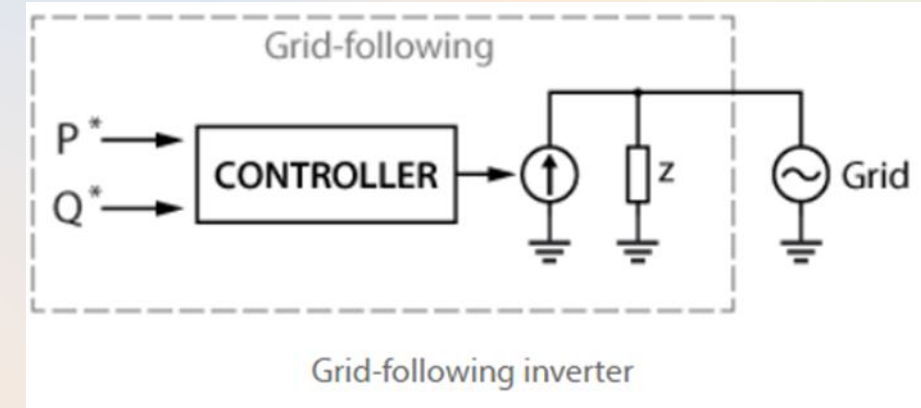
- Act as **voltage sources** that set grid voltage and frequency
- Can **anchor weak grids** and operate in **islanded microgrids**
- Continue operating during **faults and voltage sags**
- Share active and reactive power using **frequency and voltage droop**
- Provide **inertial-like response**, frequency regulation, and voltage control
- Suppress oscillations and improve stability in weak or high-X/R networks



Grid Following inverters

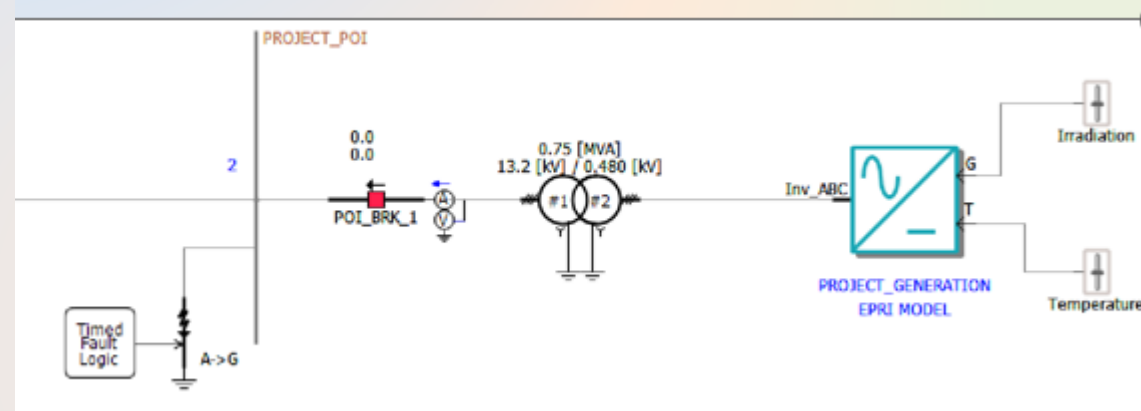
Grid-Following Inverters (GFL)

- Act as **current sources** that follow grid voltage via a phase-locked loop (PLL)
- Require a **strong, stable grid** to operate
- Cannot maintain frequency or voltage on their own
- May **disconnect during faults or deep voltage sags**
- Provide reactive power and power-factor control, but **no frequency control**
- Can amplify oscillations when many units operate together on weak feeders



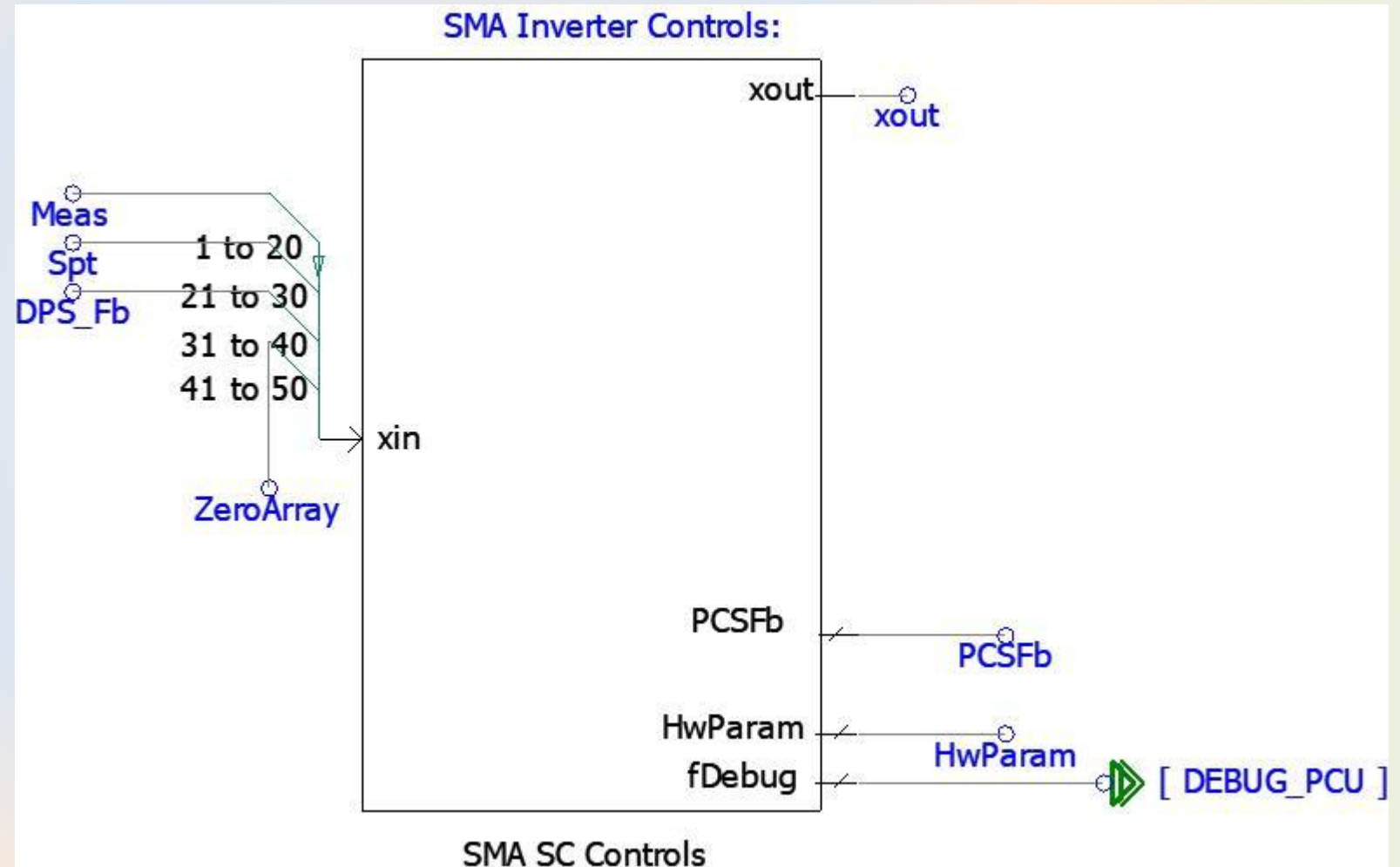
Different terminologies

- Black box models
- Volt-var
- SPOV/TPOV
- Momentary cessation
- Fast Start
- Config file
- Protections settings



Blackbox models

A black box model of an inverter is a behavioral modeling technique used in power system analysis to represent the input-output relationships of an inverter without needing knowledge of its internal circuit topology, components, or control parameters



Volt-VAR



Inverter Settings

Physical Elements

Control Elements

Active Power Support Function

Reactive Power Support Function

Inverter Inner Controls

Momentary Cessation

Enter Service Criteria

Protection Elements

Under- and Over-voltage Trip

Under- and Over-frequency Trip

Active Islanding Detection

Self-protection

General

Select the desired active power support modes (only one selection is allowed)

1. Voltage-Reactive Power (Volt-Var) Function (Default Selection)

Enable/Disable Volt-Var [Enable:1; Disable:0]

Volt-Var Curve Point V1 Setting (pu)

Volt-Var Curve Point V2 Setting (pu)

Volt-Var Curve Point V3 Setting (pu)

Volt-Var Curve Point V4 Setting (pu)

Volt-Var Curve Point Q1 Setting (pu)

Volt-Var Curve Point Q2 Setting (pu)

Volt-Var Curve Point Q3 Setting (pu)

Volt-Var Curve Point Q4 Setting (pu)

Volt-Var Open-loop Response Time (s)

2. Active Power-Reactive Power (Watt-Var) Function

Enable/Disable Watt-Var [Enable:1; Disable:0]

Watt-Var Curve Point P1 Setting (pu)

Watt-Var Curve Point P2 Setting (pu)

Watt-Var Curve Point P3 Setting (pu)

Watt-Var Curve Point Q1 Setting (pu)

Watt-Var Curve Point Q2 Setting (pu)

Watt-Var Curve Point Q3 Setting (pu)

3. Constant Power Factor Function

Enable/Disable Constant Power Factor [Enable:1; Disable:0]

Constant Power Factor Setting

Constant Power Factor Excitation [Leading:1; Lagging:-1]

4. Constant Reactive Power Mode

Enable/Disable Constant Reactive Power [Enable:1; Disable:0]

Constant Reactive Power Setting in pu [Injection: positive; Absorption:negative]

Volt-VAR

```
##### Volt-VAR control enable#####
GriMng_InvVarMod          GRIMNG_INVVARMOD_VARCTLVOL      # Reactive power as a function of voltage / GRIMNG_INVVARMOD_OFF: off / GRIMNG_INVVARMOD_VARCTLVOL: Q/V function

VArCtlVol_VArSptFilTm      0.01

VArCtlVol_HiGra3           0.0          # 2 decimal places possible for gradients (Range: [0.0 ...10.0])
VArCtlVol_HiGra2          11.0          # 2 decimal places possible for gradients (Range: [0.0 ...10.0])
VArCtlVol_HiGra1           0.0          # 2 decimal places possible for gradients (Range: [0.0 ...10.0])
VArCtlVol_LoGra1           0.0          # 2 decimal places possible for gradients (Range: [0.0 ...10.0])
VArCtlVol_LoGra2          11.0          # 2 decimal places possible for gradients (Range: [0.0 ...10.0])
VArCtlVol_LoGra3           0.0          # 2 decimal places possible for gradients (Range: [0.0 ...10.0])

VArCtlVol_HiVolRef3        1.07          # 3 decimal places possible for gradients (Range: [0.0 ...10.0])
VArCtlVol_HiVolRef2        1.03          # 3 decimal places possible for gradients (Range: [0.0 ...10.0])
VArCtlVol_LoVolRef1HiVolRef1 1.0          # 3 decimal places possible for gradients (Range: [0.0 ...10.0])
VArCtlVol_LoVolRef2        0.97          # 3 decimal places possible for gradients (Range: [0.0 ...10.0])
VArCtlVol_LoVolRef3        0.93          # 3 decimal places possible for gradients (Range: [0.0 ...10.0])

VArCtlVol_VolNomSptMod     VOLNOMSPTMOD_INVMS_VOLPSNOM      # Selector for the voltage setpoint / #VOLNOMSPTMOD_VOLNOMSPT: Set-point / #VOLNOMSPTMOD_INVMS_VOLPSNOM:
Filtered measurement value
VArCtlVol_VolFilTm         0.5
VArCtlVol_VolPsNomHiLim    1.1
VArCtlVol_VolPsNomLoLim    0.9

#####
WctlHzMod                 SWITCH_STT_DISABLE      # Active Power as a function of frequency for PV: Mode over frequency / SWITCH_STT_DISABLE: off /
SWITCH_STT_ENABLE: on
WctlHzBatMod              SWITCH_STT_DISABLE      # Active Power as a function of frequency for BESS: Mode over frequency / SWITCH_STT_DISABLE: off /
SWITCH_STT_ENABLE: on
WctlHzLoHiMod             SWITCH_STT_DISABLE
```

Momentary Cessation

Inverter Settings

Physical Elements

Control Elements

- Active Power Support Function
- Reactive Power Support Function
- Inverter Inner Controls
- Momentary Cessation**
- Enter Service Criteria

Protection Elements

- Under- and Over-voltage Trip
- Under- and Over-frequency Trip
- Active Islanding Detection
- Self-protection

General	
Enable/Disable momentary cessation [Enable:1; Disable:0]	1
High-voltage momentary cessation threshold voltage (pu)	1.1
Low-voltage momentary cessation threshold voltage (pu)	0.5

Inverter Settings

- Physical Elements
- Control Elements
 - Active Power Support Functions
 - Reactive Power Support Functions
 - Inverter Inner Controls
 - Momentary Cessation
 - Enter Service Criteria
- Protection Elements
 - Under- and Over-voltage Trip Elements
 - Under- and Over-frequency Trip Elements
 - Active Islanding Detection
 - Self-protection**

General	
Enable/Disable self-protection [Enable:1; Disable:0]	0
Instantaneous over-voltage protection	
Transient over-voltage must trip curve point TOV4 voltage setting (pu)	2
Transient over-voltage must trip curve point TOV4 duation setting (s)	0.0016
Transient over-voltage must trip curve point TOV3 voltage setting (pu)	1.7
Transient over-voltage must trip curve point TOV3 duration setting (s)	0.003
Transient over-voltage must trip curve point TOV2 voltage setting (pu)	1.4
Transient over-voltage must trip curve point TOV2 duration setting (s)	0.016
Transient over-voltage must trip curve point TOV1 voltage setting (pu)	1.3
Transient over-voltage must trip curve point TOV1 duration setting (s)	0.166
Over-current protection	
Over-current must trip curve point OC2 current setting (pu)	2
Over-current must trip curve point OC2 duration setting (s)	0.16
Over-current must trip curve point OC1 current setting (pu)	1.5
Over-current must trip curve point OC1 duration setting (s)	0.5

These mechanisms, referred to as SPOV mechanisms cause the inverter to cease to energize when the circuit voltage exceeds certain limits. The SPOV mechanisms thus can prevent both ground fault overvoltage (GFOV), and load-rejection overvoltage (LROV). Normally the voltage range is between 1.2 to 1.4 pu while the time threshold that the inverter can tolerate is about a few milliseconds.

The Manufacturer should issue a letter confirming the inverter model has user adjustable SPOV settings with required threshold time to trip? The SPOV setting should be adjustable in the PSCAD model.

Under and Over Voltage Trip Elements

Inverter Settings

- Physical Elements
- Control Elements
 - Active Power Support Functions
 - Reactive Power Support Functions
 - Inverter Inner Controls
 - Momentary Cessation
 - Enter Service Criteria
- Protection Elements
 - Under- and Over-voltage Trip Elements
 - Under- and Over-frequency Trip Elements
 - Active Islanding Detection
 - Self-protection

Instantaneous over-voltage protection		
Enable/Disable instantaneous over-voltage protection [Enable:1; Disable:0]		1
Transient over-voltage must trip curve point TOV4 voltage setting (pu)		2
Transient over-voltage must trip curve point TOV4 duration setting (s)		0.0016
Transient over-voltage must trip curve point TOV3 voltage setting (pu)		1.7
Transient over-voltage must trip curve point TOV3 duration setting (s)		0.003
Transient over-voltage must trip curve point TOV2 voltage setting (pu)		1.4
Transient over-voltage must trip curve point TOV2 duration setting (s)		0.016
Transient over-voltage must trip curve point TOV1 voltage setting (pu)		1.3
Transient over-voltage must trip curve point TOV1 duration setting (s)		0.166
RMS-based under- and over-voltage protection		
High voltage must trip curve point OV2 voltage setting (pu)		1.2
High voltage must trip curve point OV2 duration setting (s)		0.16
High voltage must trip curve point OV1 voltage setting (pu)		1.1
High voltage must trip curve point OV1 duration setting (s)		13
Low voltage must trip curve point UV1 voltage setting (pu)		0.88
Low voltage must trip curve point UV1 duration setting (s)		21
Low voltage must trip curve point UV2 voltage setting (pu)		0.5
Low voltage must trip curve point UV2 duration setting (s)		2

```
Vctl_Lo1Lim 0.9
Vctl_Lo2Lim 0.7
Vctl_Lo3Lim 0.7
Vctl_Lo4Lim 0.7
Vctl_Lo5Lim 0.45
Vctl_Lo1LimTm 2000
Vctl_Lo2LimTm 1000
Vctl_Lo3LimTm 1000
Vctl_Lo4LimTm 1000
Vctl_Lo5LimTm 160
Vctl_Hi1Lim 1.1
Vctl_Hi2Lim 1.1
Vctl_Hi3Lim 1.1
Vctl_Hi4Lim 1.1
Vctl_Hi5Lim 1.2
Vctl_Hi1LimTm 2000
Vctl_Hi2LimTm 2000
Vctl_Hi3LimTm 2000
Vctl_Hi4LimTm 2000
Vctl_Hi5LimTm 160
```

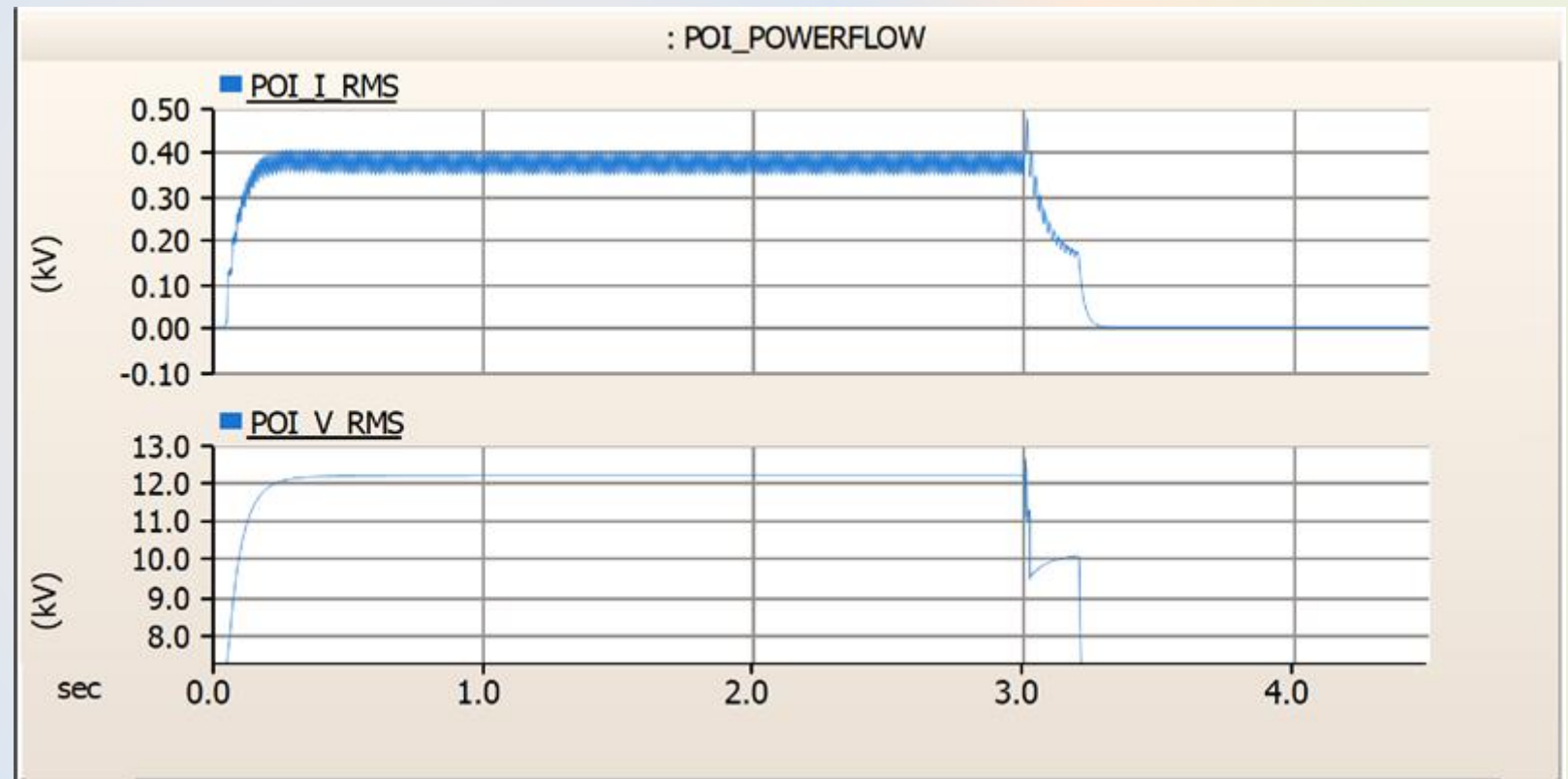
Fast Start

Fast Start configuration window:

General	
Filenumber	10
Inverter name	PCU1
type of SC inverter	SCS 3450 UP-XT-US
Country set	US HECO
Enable file logging	0
FastStart (time in ms until FastSt	250
Output to DPS	DPS1_Spt
Input from DPS	DPS_Fb
DEBUG_PCU signals	DEBUG_PCU1
MEAS_PCU signals	MEAS_PCU1

FastStart (time in ms until FastStart is finished)
Type=Integer, Symbol=FastStart, min=0, max=2147483...

Ok Cancel Help...



Are Inverters grounded?

- PV inverters operate as balanced three-phase current sources
- A neutral conductor is not required for power export
- Therefore, most PV inverters do not provide a neutral terminal
- Omitting the neutral helps avoid transient neutral currents caused by brief phase imbalances
- A solid neutral connection can interfere with voltage fault detection
- It may also cause nuisance circulating currents in isolation transformers

Glimpse of inverter from RMS model

Electronically Coupled Generator - At To Node

Id:
Number:
Status:
Location: Stage:

Inverter

☐ Inverter ID:

Manufacturer:
Model:
Standard:
☒ Single-phase
☐ Three-phase

Efficiency: %
Internal Losses: W /phase

DC side
Rated DC Voltage (Vdc): kV
☐ DC Capacitor (Cdc): μ F

AC side
Nominal Rating: kVA /phase
Active Power Rating: kW /phase
Reactive Power Rating: kvar /phase
Min Power Factor: +/- %
☒ Internal Coupling Element
Coupling Resistance (R): Ω
Coupling Inductance (L): H

OK

Cancel

Inverter Controls

Grid Management Limitations

Control Type	Mode	Settings
Adjust Power Factor	INV3 - Adjust Power Factor	100.0 %
+ Add new inverter control		

☒ Validate

Rise and Fall Limitations

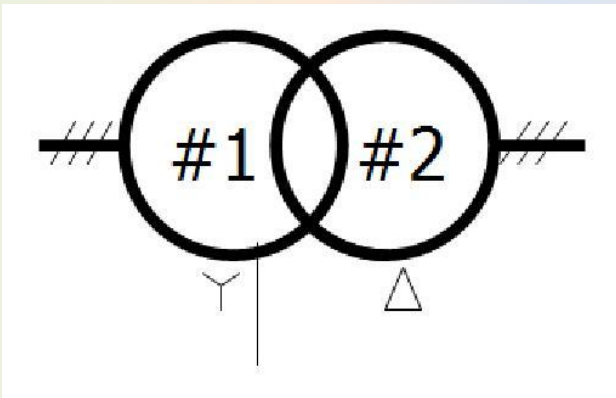
☐ Rise Limit: %/min
☐ Fall Limit: %/min

Time Delay

☐ Generation Delay: s

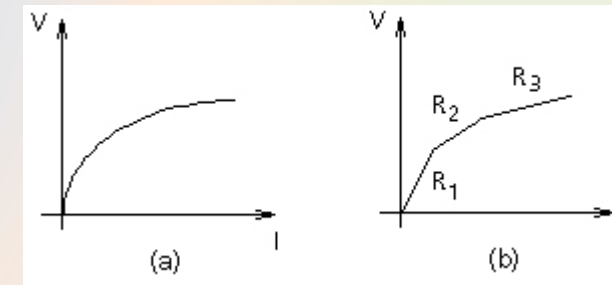
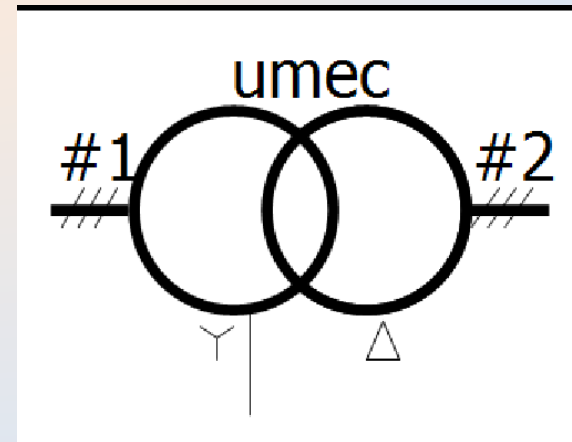
Classical Model

- Limited to **single-phase units**
- Windings are assumed to be on the **same core leg**
- Core non-linearity is approximated using:
 - Knee point
 - Air-core reactance
 - Magnetizing current at rated voltage
- Support **online tap changers** with dynamic adjustment



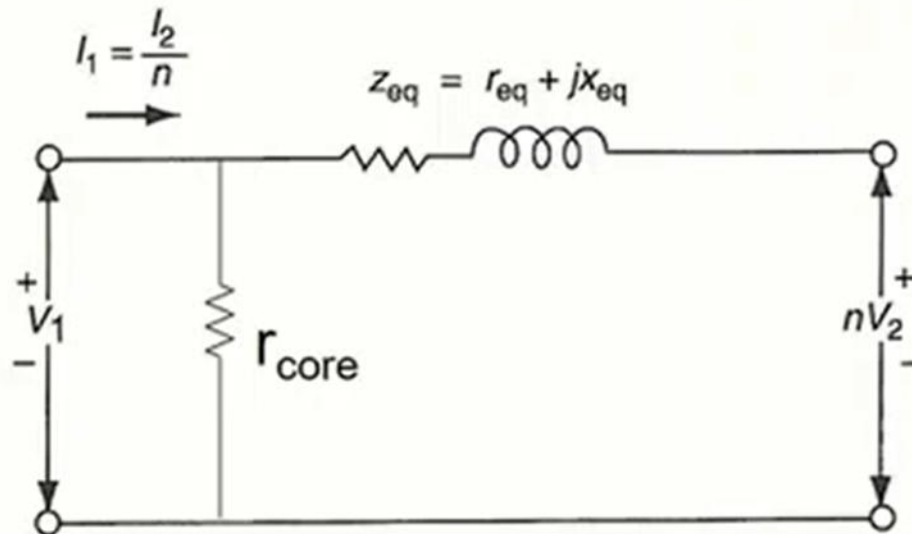
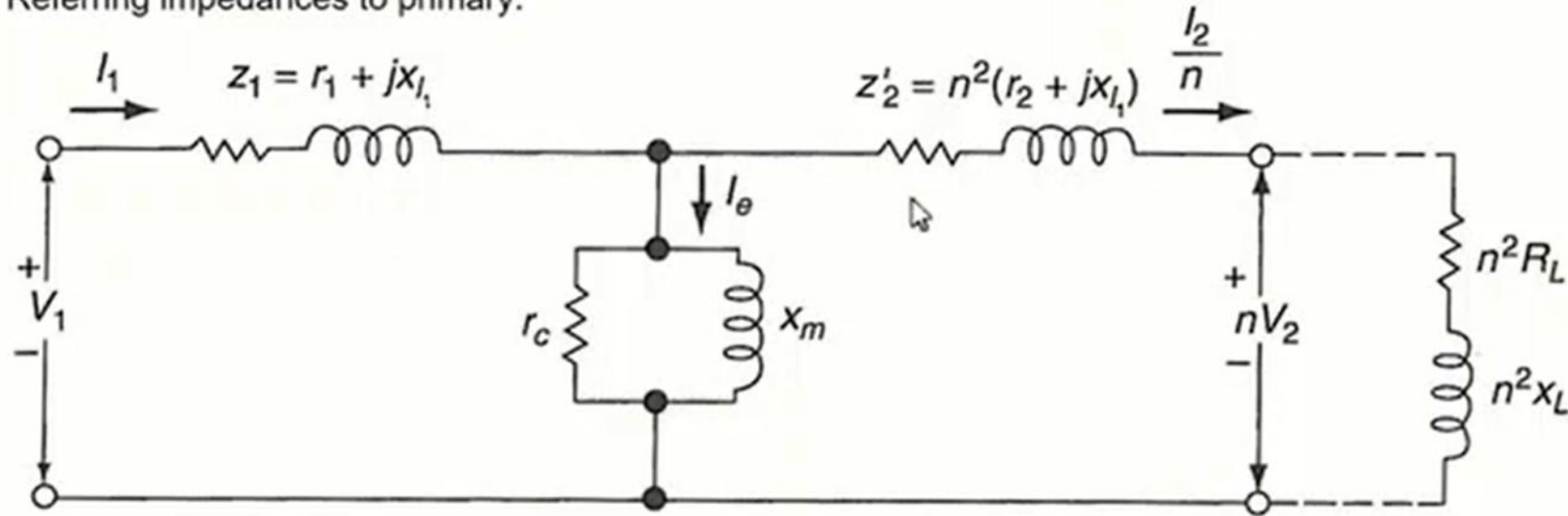
UMEC Transformer Models

- Represent **actual core geometry**
- Include **inter-phase magnetic coupling**
- Core non-linearity is modeled directly using a **V-I curve**
- Tap settings can be defined on a winding
- **No online tap changer** (tap position cannot change during simulation)



Properties of transformer

Referring impedances to primary:



$$r_{eq} = r_1 + n^2 r_2$$

$$X_{eq} = X_1 + n^2 X_2$$

Modelling of transformer

3 Phase 2 Winding Transformer

Configuration

- Winding Voltages
- Saturation
- Magnetic Characteristics of the M...
- Winding 1 Currents
- Winding 2 Currents
- Monitoring of Magnetic Core:1
- Monitoring of Magnetic Core:2

General

Transformer Name	PCU2_TRF_1
3 Phase Transformer MVA	3.425 [MVA]
Base Operation Frequency	60.0 [Hz]
Winding #1 Type	Y
Winding #2 Type	Y
Delta Lags or Leads Y	Lags
Positive Sequence Leakage Reactance	0.058177 [pu]
Ideal Transformer Model	Yes
Eddy Current Losses	0.001 [pu]
Copper Losses	0.001304 [pu]
Tap Changer on Winding	None
Graphics Display	Single line (circles)
Display Details?	No

General

Ok Cancel Help...

3 Phase 2 Winding Transformer

Configuration

- Winding Voltages
- Saturation
- Magnetic Characteristics of the M...
- Winding 1 Currents
- Winding 2 Currents
- Monitoring of Magnetic Core:1
- Monitoring of Magnetic Core:2

General

Saturation Enabled	Yes
Place Saturation on Winding	Middle
Hysteresis	Basic model
Inrush Decay Time Constant	0.0 [s]
Time to Release Flux Clipping	0.0 [s]
Air Core Reactance	0.14 [pu]
Magnetizing Current	1 [%]
Knee Voltage	1.24 [pu]
Remanent Flux Core 1	0.7
Remanent Flux Core 2	0.0
Remanent Flux Core 3	-0.7
Loop Width	10
Nominal Flux Density [T]	1.7
Magnetic Material	default

General

Ok Cancel Help...

Properties of transformer

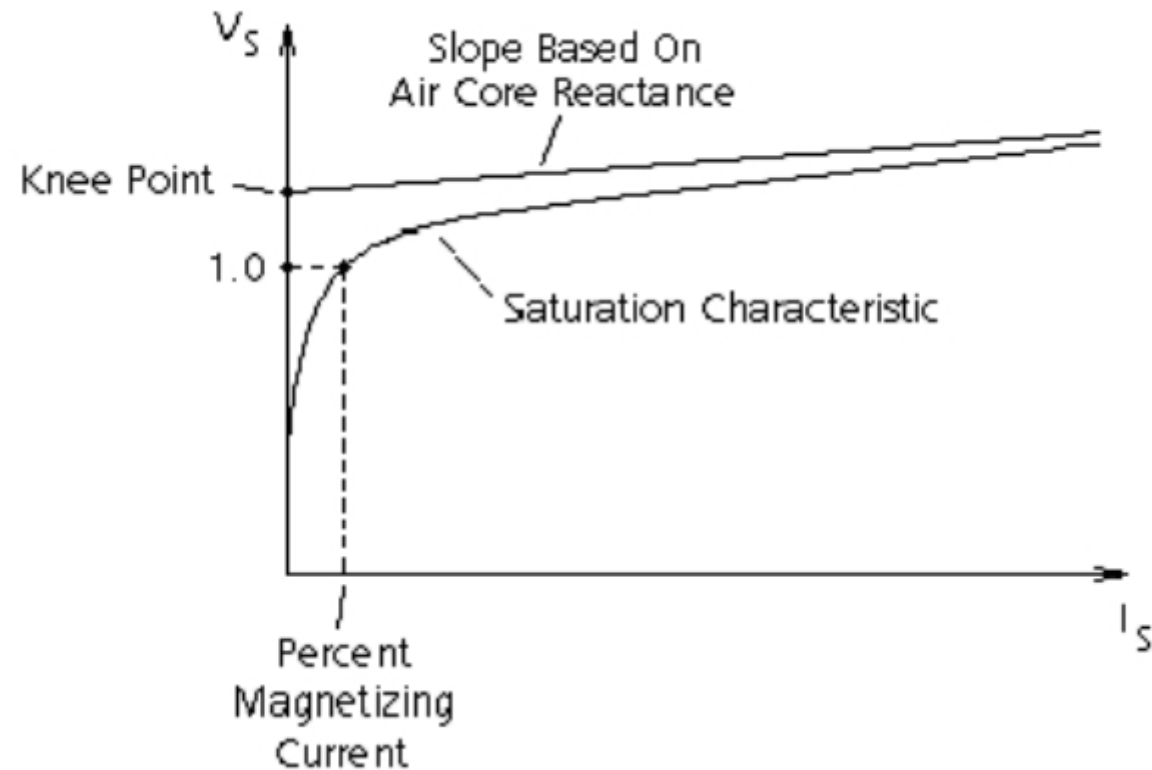
Air-core reactance $\approx 2 * \text{leakage reactance}$
Magnetizing current at rated voltage $\approx 1\%$
Eddy current loss = no load loss

Ideal Transformer

- Only leakage reactance
- No magnetizing branch

Core loss is modelled as equivalent shunt reactance.

- Air Core Reactance adjusts the slope of the asymptotic line
- Knee Voltage shifts the Y-intercept of the asymptotic line
- Magnetizing Current set the horizontal position of the knee point; higher values make saturation less sharp



Transformer in RMS model

Two-Winding Transformer - At From Node

Id: Failures...

Number:

Status: ☒ Reversible

Location: Stage:

Settings

General

Primary:

Fault indicator:

De-energized Tap Changer

Primary Tap: % kVLL

Secondary Tap: % kVLL

Grounding Impedances

	Rg	Xg	
Primary:	0.0	0.0	Ω
Secondary:	0.0	0.0	Ω

Configuration

Primary:

Secondary:

Phase Shift:

Gamma Phase Shift:

Open Branch:

Center Tap Phase:

Protection

System Nominal Voltage

Primary:	13.2 kVLL	☐ User defined
Secondary:	4.8 kVLL	☐ User defined

OK Cancel

General Loading Limits LTC Reliability Symbol

Nominal Data

Transformer Type:

Insulation Type:

Winding Type:

Nominal Rating: kVA

Primary Voltage: kVLL

Secondary Voltage: kVLL

No Load Losses: kW

Magnetizing Current: %

Configuration

Primary:

Secondary:

Phase Shift:

☒ Reversible

Impedance

Z: % X/R:

Grounding Impedances

	Rg	Xg	
Primary:	0.0	0.0	Ω
Secondary:	0.0	0.0	Ω

OK Cancel

Conductors

Section Properties

Section ID: 431

Phase: ☒ A ☒ B ☒ C

Zone: UNDEFINED

Environment: Unknown

Devices: Add Remove

Cable Type: Cable

Number: 431

Status: Connected

Length: 72.9686 ft

Stage: Undefined

Settings

Configuration

Cable ID: GC 15KV 1/0AWG 1C CU

Neutral 1 ID: ☐ Cable DEFAULT

Neutral 2 ID: ☐ Cable DEFAULT

Neutral 3 ID: ☐ Cable DEFAULT

In Parallel: 1

Overview

Cable Type: 1C

Conductor Material: ALUMINUM

Conductor Size: 1/0 AWG

Insulation Type: XLPE_FILLED

Operating Condition

Operating Temp.: 90.0 °C

Protection

TCC Settings...

OK Cancel

Section Properties

Section ID: 431

Phase: ☒ A ☒ B ☒ C

Zone: UNDEFINED

Environment: Unknown

Devices: Add Remove

Cable Type: Cable

Number: 431

Status: Connected

Length: 72.9686 ft

Stage: Undefined

Equivalent Impedances

☐ Phase Impedances ☒ Sequence Impedances

R + jX Ω/mi G + jB $\mu\text{S}/\text{mi}$

Positive Sequence: 1.203 + j0.4109 0 + j125.7

Zero Sequence: 1.822 + j0.3114 0 + j125.7

OK Cancel

SN	Cable Type	Voltage (kV)	Positive Sequence Impedance (Ohm/mile)		Zero Sequence Impedance (Ohms/mile)		Positive sequenace Susceptance B1 ($\mu\text{S}/\text{mile}$)	Zero Sequence Susceptance B0 ($\mu\text{S}/\text{mile}$)	Positive Sequence Capacitive reactance Xc1 (Mohm.mile)	Zero Sequence Capacitive reactance Xc0 (Mohm.mile)
			R1	X1	Ro	Xo				
2	1/0AL XLPE , UG	13.2	0.1893	0.0898	0.3505	0.084	21.077	0	0.047445082	#DIV/0!
2	#2 AL, UG	13.2	1.076	0.2428	2.929	1.668	100.5	100.5	0.009950249	0.009950249
3	3-477 AAC, 3/0 ACSR Neut, OH	13.2	0.1975	0.6419	0.6041	2.073	6.787	2.941	0.147340504	0.340020401
4	3-477 AAC, 4/0 ACSR Neut, OH	13.2	0.1975	0.6419	0.5457	2.044	6.787	2.942	0.147340504	0.339904827

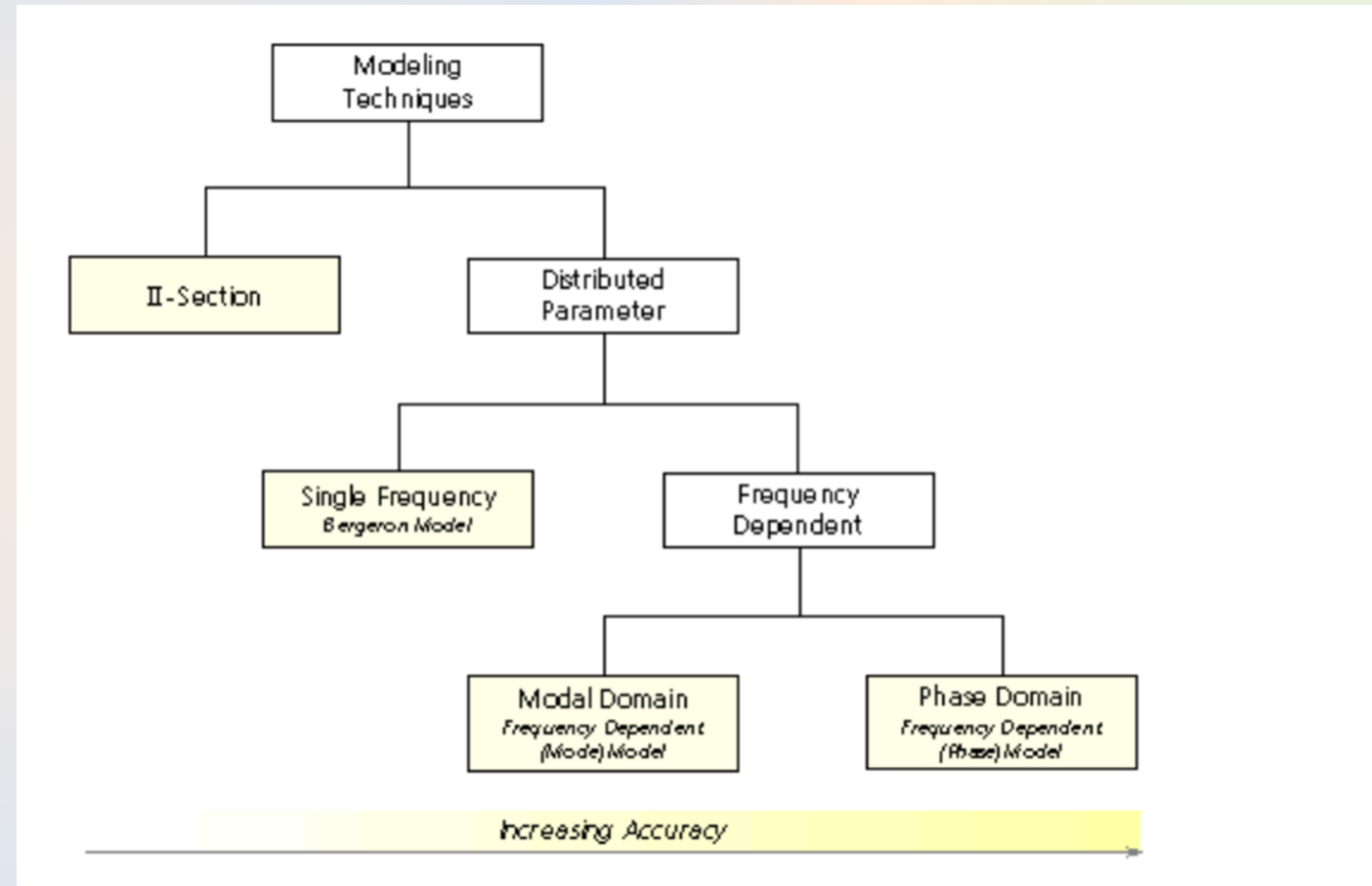
Pi- section is suitable for very short lines where the travelling wave models cannot be used, due to time step constraints

Bergeron Model

- Distributed L and C; lumped R (1/2 at mid point, 1/4 at end)
- Equivalent to infinite p -sections
- Accurate at fundamental frequency
- Can approximate limited high-frequency attenuation
- Fast computational performance

Frequency-Dependent Models

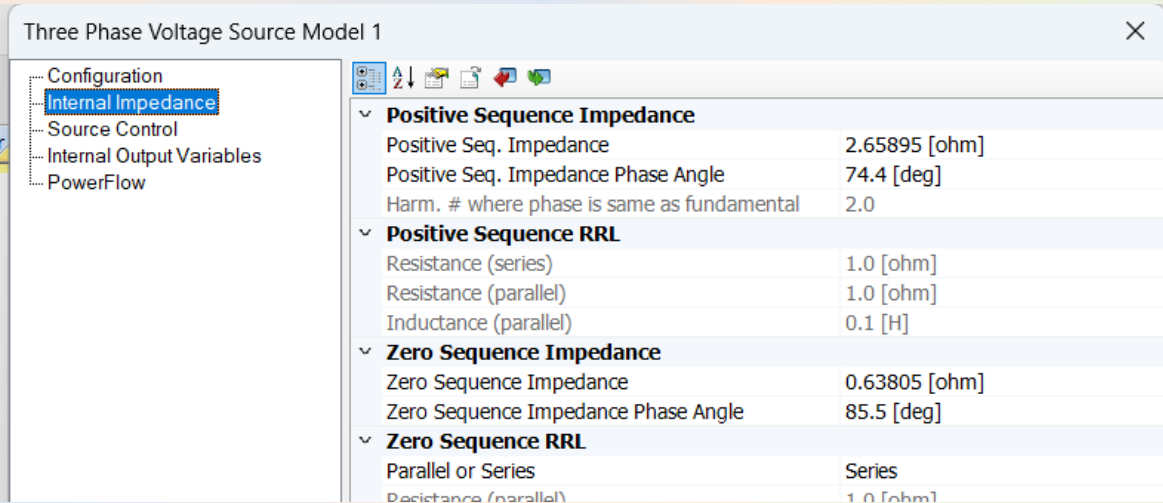
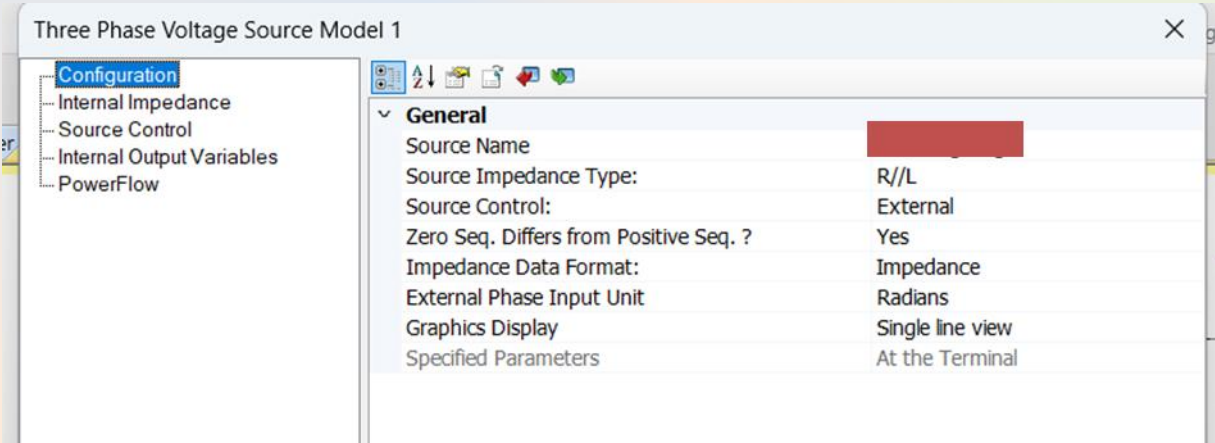
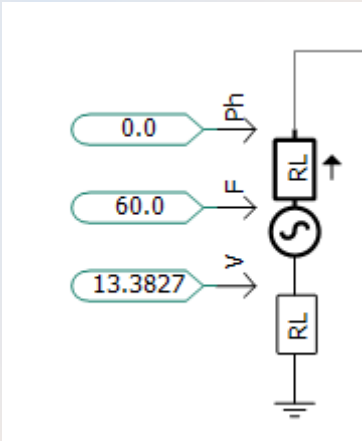
- Distributed R, L, and C
- Solved over multiple frequency points
- More accurate attenuation across wide frequency range
- Slower than Bergeron model
- FD (Phase) model supports all line types and asymmetry



Source: PSCAD Knowledge base

Station Modelling

Station is modelled as voltage-source.



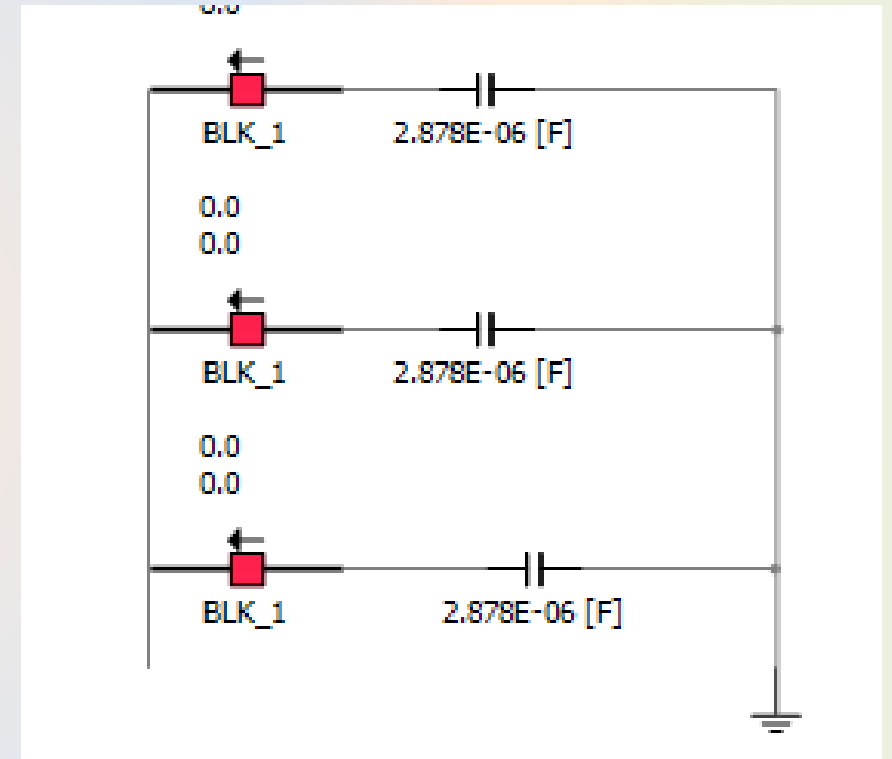
Capacitor banks

Each breaker is controlled by sensing the voltage or var at the remote or local location.

If the voltage is less V_{low} , the cap bank turns ON.

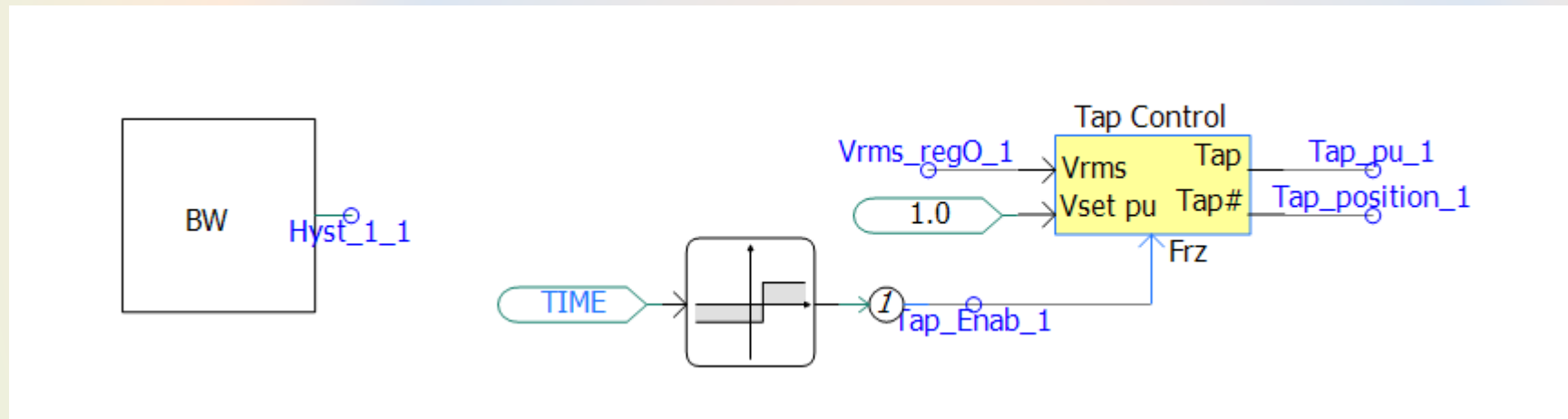
If the voltage is greater than V_{high} , the cap bank turns OFF.

If the voltage is between V_{low} and V_{high} , no change of status.



Regulators

Combine the tap changing logic with the transformer block.



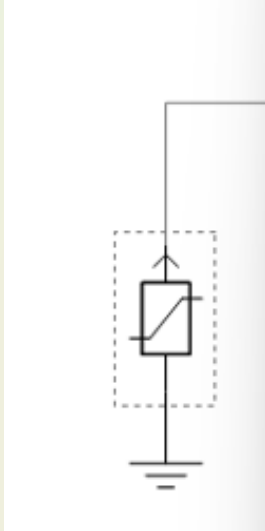
Rated Voltage

- Defines the Temporary Overvoltage (TOV) handling capability.
- Specifies the maximum voltage sustained for 10 to 100 seconds.

Maximum Continuous Operating Voltage (MCOV)

- The maximum power frequency voltage the arrester can handle indefinitely.
- IEC 60099-5 Requires MCOV to be at least 5% higher than the system's highest continuous operating voltage.

Surge Arrestors



Arrester

Configuration

- I-V Characteristic (Current)
- I-V Characteristic (Voltage)

_General

Arrester Name	
Arrester Voltage Rating	12 [kV]
Number of Parallel Arrester Stacks	3
Enable Non-Linear Characteristic	1
I-V Characteristic	User defined (external data file)

External Data File

File Name	datafile
Path to the Data File is given as	Relative pathname
Maximum Number of Points in the File	25

Outputs

Label for Current [kA]	Isa
Label for Energy [kJoules]	Esa

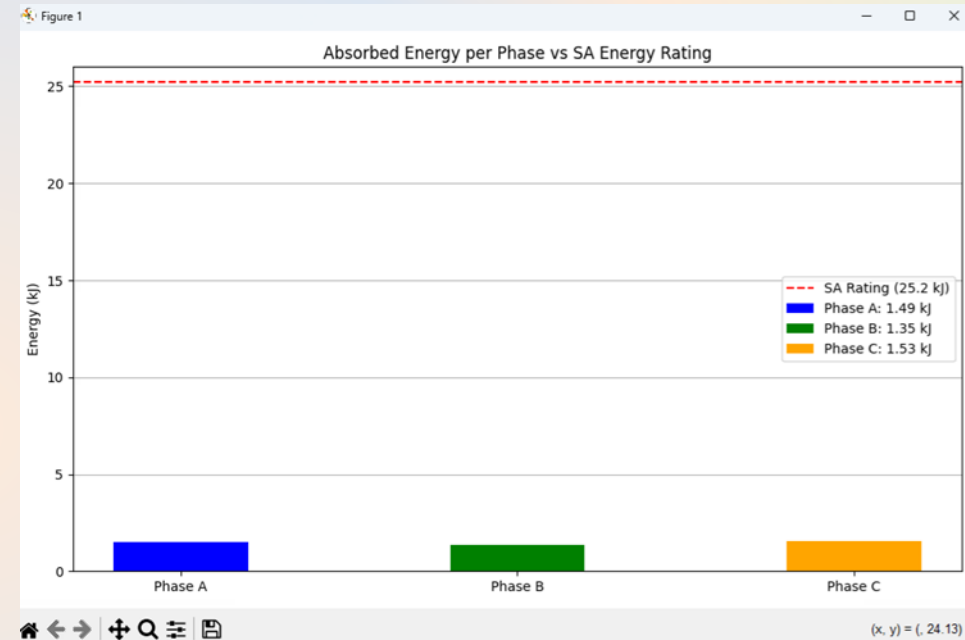
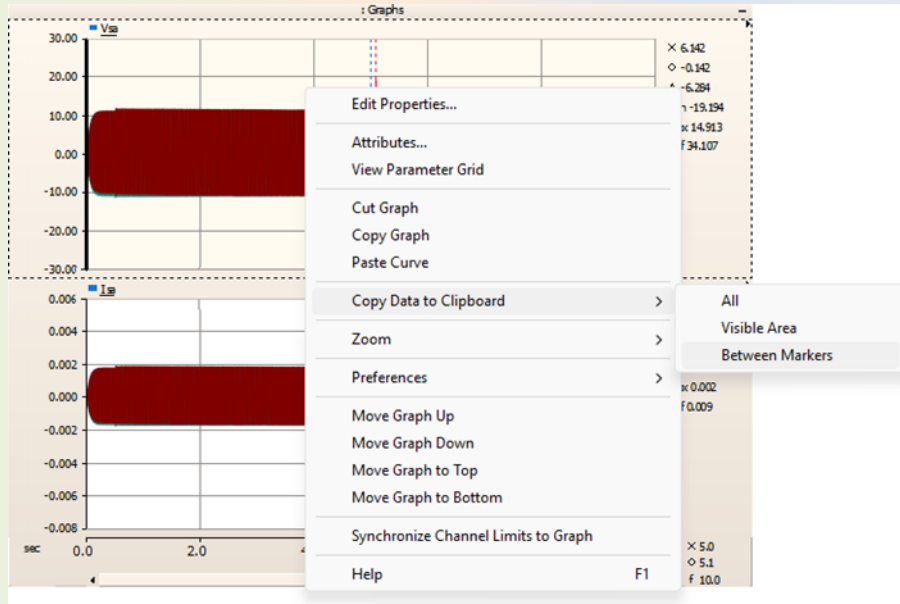
_General

Ok Cancel Help...

Data Points - Current	
Point 1 - Current	0.001 [kA]
Point 2 - Current	0.01 [kA]
Point 3 - Current	0.1 [kA]
Point 4 - Current	0.125 [kA]
Point 5 - Current	0.2 [kA]
Point 6 - Current	0.5 [kA]
Point 7 - Current	1.5 [kA]
Point 8 - Current	3 [kA]
Point 9 - Current	5 [kA]
Point 10 - Current	10 [kA]
Point 11 - Current	20 [kA]

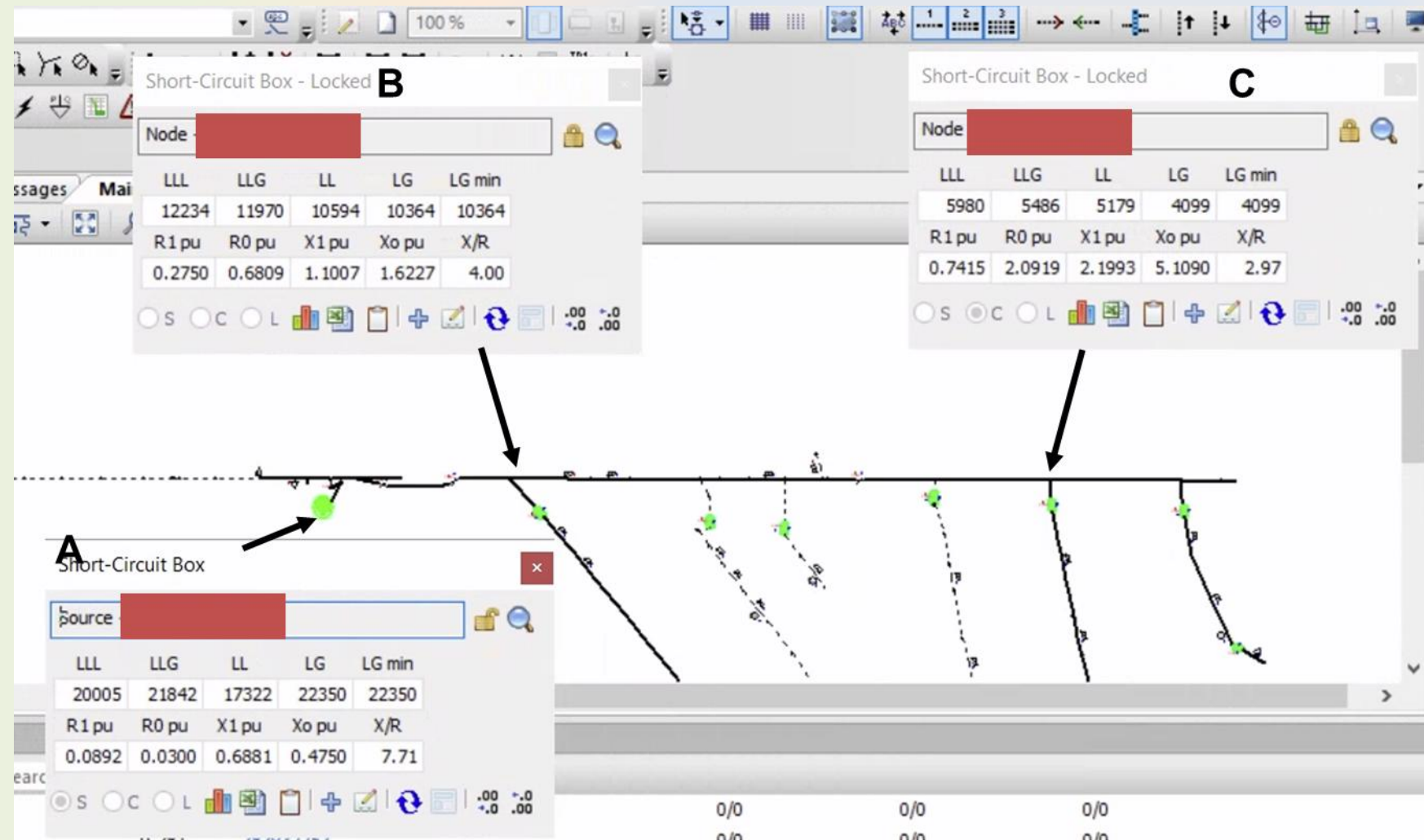
Data Points - Voltage	
Point 1 - Voltage in pu	1.1 [pu]
Point 2 - Voltage in pu	1.6 [pu]
Point 3 - Voltage in pu	1.7957 [pu]
Point 4 - Voltage in pu	1.85 [pu]
Point 5 - Voltage in pu	1.90 [pu]
Point 6 - Voltage in pu	1.95 [pu]
Point 7 - Voltage in pu	2.125 [pu]
Point 8 - Voltage in pu	2.225 [pu]
Point 9 - Voltage in pu	2.325 [pu]
Point 10 - Voltage in pu	2.5 [pu]
Point 11 - Voltage in pu	2.8 [pu]

Energy absorbed by surge arrester

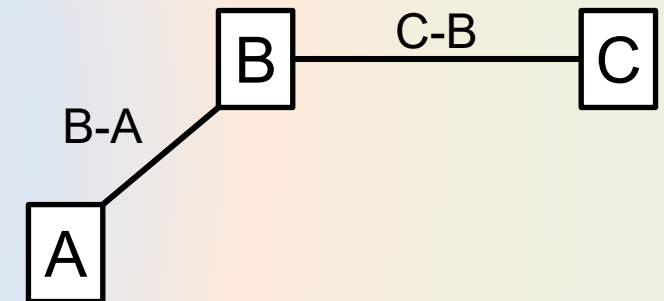


$$\text{Energy (kJ)} = \sum (\text{Voltage (kV)} \times \text{Current (kA)}) \times \Delta t \times 1000$$

Modelling cable and OH conductor



Impedance is calculated by getting difference between downstream node and upstream node with no gen connected to the circuit.



Configuring PSCAD, revisiting inverter blackbox model

File		Home		Project		View		Tools		Components		Models	
Namespace	CDG_00398_GFL_rev4	 Settings		Duration of Run (s)	5	Startup Method	Standard	Output Method	None	None			
Description				Solution Time Step (us)	5					test.snp			
Path	..\..\K&A\Distribution Planning			Channel Plot Step (us)	200		C:\Users\HivaNasiri\K&A\Dist ...	HyCon_Demo.out	Time	9.0			
General Settings				Runtime				Startup		Output		Snapshots	

Black box models have requirement for minimum solution time step. If the time step is greater than specified time step, the result may be erroneous.

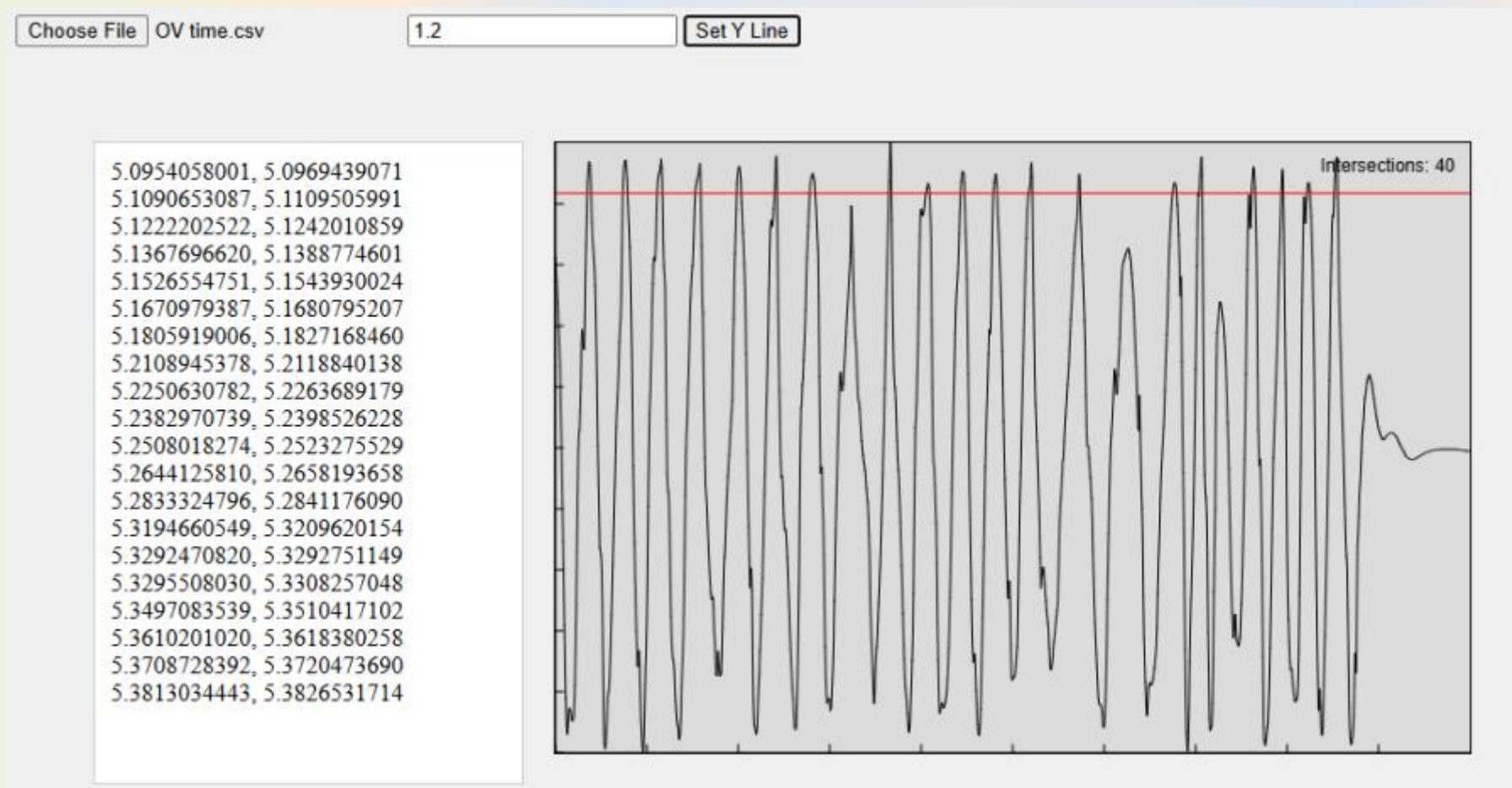
Sequence of events GFOV

- Apply Single Line Ground fault at project's POI (Point of Interconnection) on one of the
- phases. We select the phase with highest DG/load ratio.
- Open the feeder breaker and/or substation breaker after 5 cycles.
- Measure voltage at the project's POI once the island is formed.
- Continue recording voltage until the project trips.
- If the voltage is not within IEEE 1547-2018 standard section 7.4.2, there are TOV violations and require mitigation.

Sequence of events LROV

- Open feeder breaker and/or substation breaker.
- Measure voltage at the project's POI once the island is formed.
- Continue recording voltage until the project trips.
- If the voltage is not within IEEE 1547-2018 standard section 7.4.2, there are TOV violations and require mitigation.

Measuring cumulative time





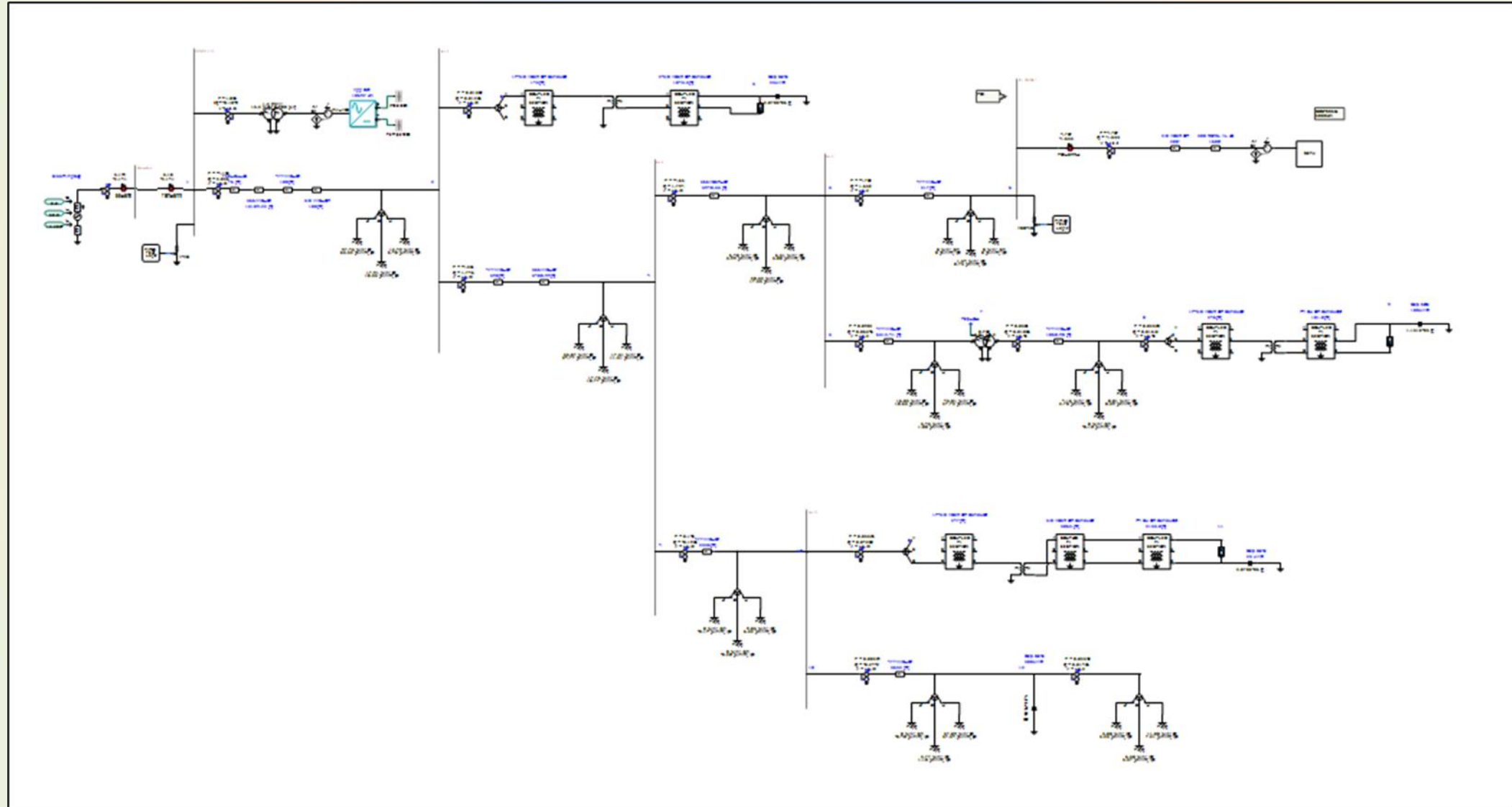
Source Modelling

```

Summary of fault being displayed:
Prefault voltage: From a linear network solution
Generator impedance: Subtransient
MOV iteration: [ On]
Enforce generator current limit [ A]
Voltage controlled current source simulated [Yes]
Type-3 wind plant simulated [No]
Converter-interfaced resource simulated [Yes]
ANSI x/r ratio calculation [ On]
  In X-only network when X=0 use X=0.0001 p.u.
  In R-only network when R=0 compute R using method 1
    with Rc=0.0002 p.u. X/R =125 for generators; =60 for transformers; =10 for reactors; =10 for others
  Assume Z2 to be same as Z1 for generators and phase shifters.
Ignore shunts with + seq value: [Yes]
Ignore loads: [Yes]
Ignore line G+jB: [Yes]
    
```

=====											
1. Bus Fault on:				13.2 kV 3LG							
						FAULT CURRENT (A @ DEG)					
						0 SEQ		A PHASE		B PHASE	
						0.00@ 0.0		2889.2@-104.2		2889.2@ 135.8	
										C PHASE	
										2889.2@ 15.8	
						THEVENIN IMPEDANCE (OHM)					
						0.71444+j2.56117 0.71446+j2.56128 0.05053+j0.63605					

PSCAD Model

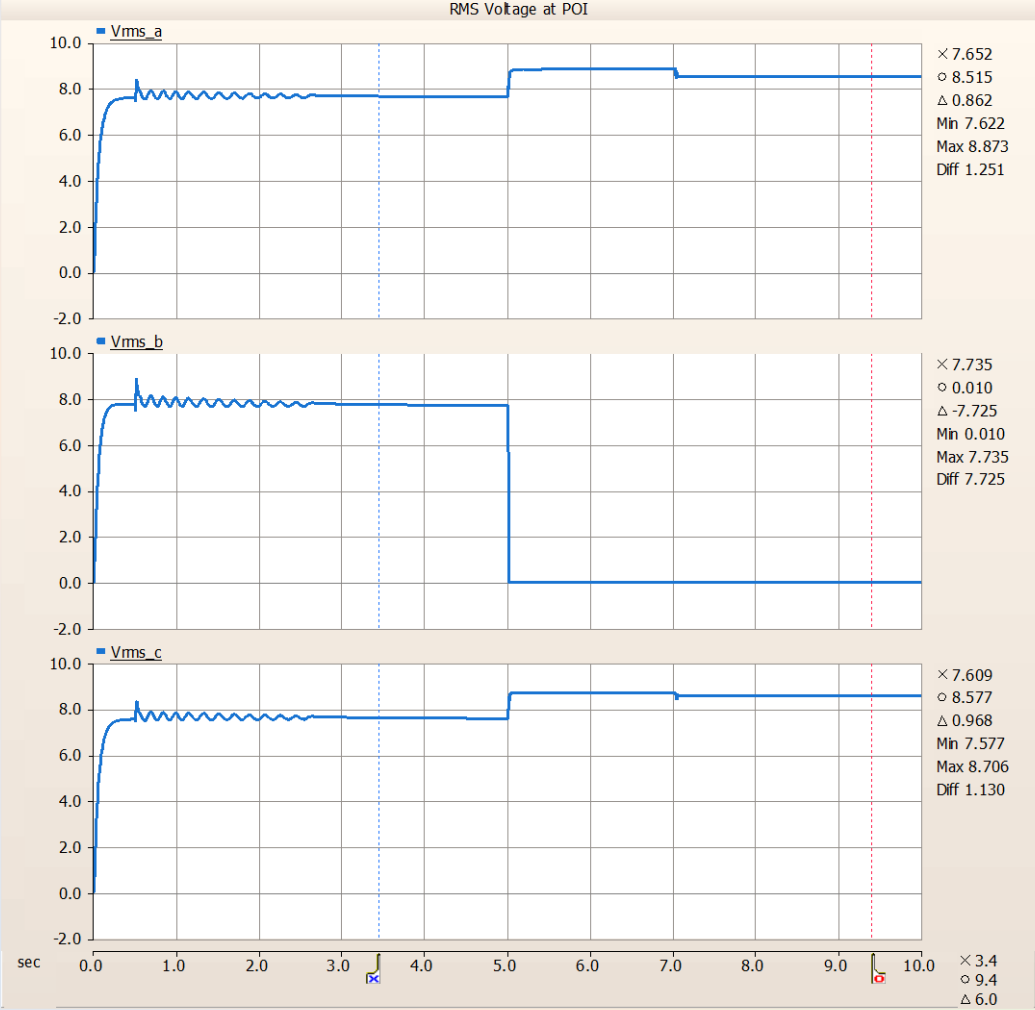
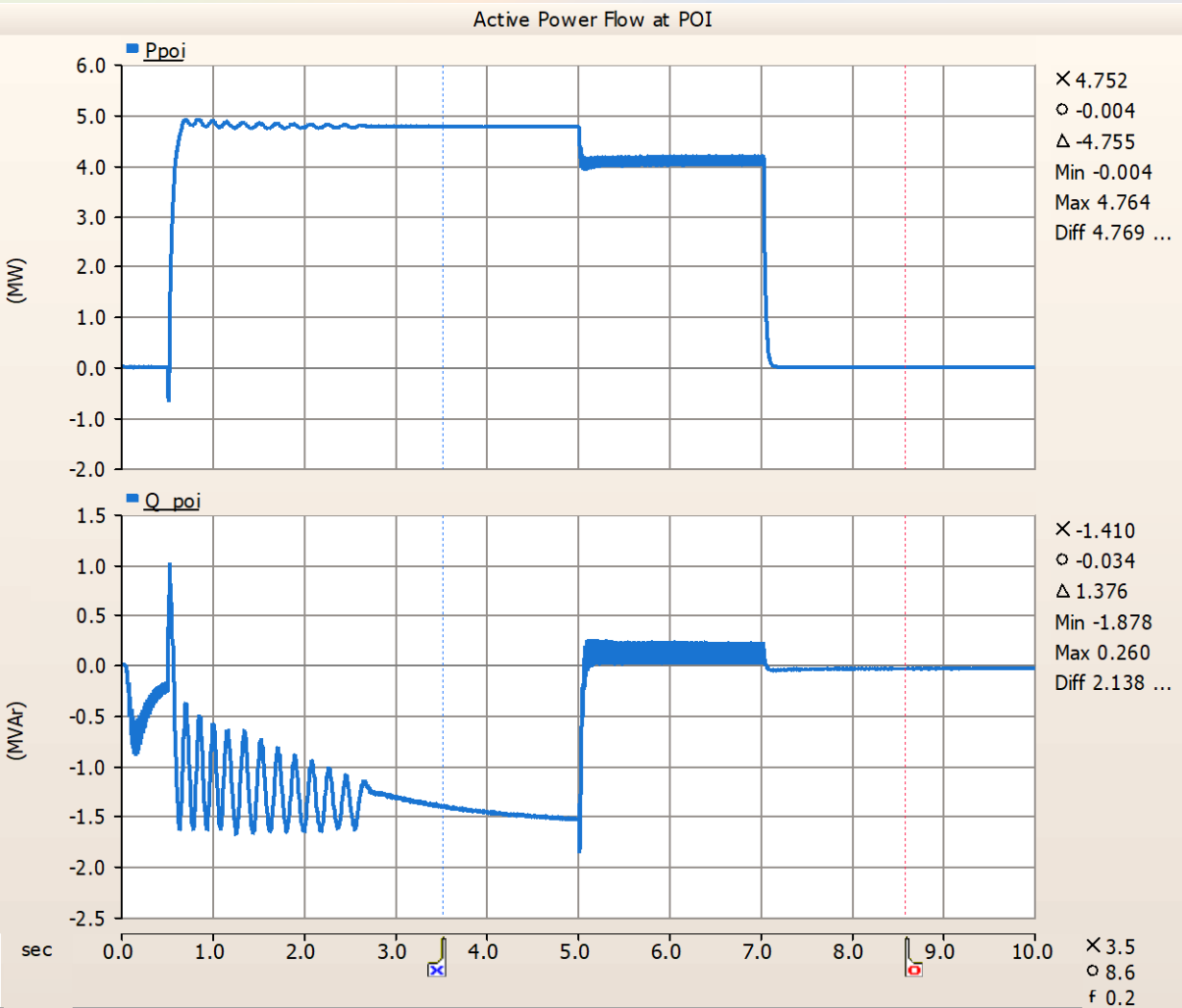


Validation Results

Location	Load Flow Values in DEW			Load Flow Values in PSCAD			Pdiff	% P Difference	Qdiff	% Q Difference	% V Difference
	P (MW)	Q (MVar)	V (kV)	P (MW)	Q (MVar)	V (kV)					
Section 1-2	0.51707	0.33185	13.428	0.52780	0.33550	13.340	-0.011	-2.08%	-0.004	-1.10%	0.65%
Section 2-3	0.01707	0.01135	13.365	0.01804	0.01437	13.260	-0.001	-5.68%	-0.003	-26.61%	0.78%
Section 2-4	0.37080	0.23685	13.365	0.37590	0.23400	13.260	-0.005	-1.38%	0.003	1.20%	0.78%
Section 4-5	0.13309	0.08368	13.343	0.13350	0.08827	13.240	0.000	-0.31%	-0.005	-5.49%	0.77%
Section 5- 6	0.00134	0.00070	13.339	0.00126	0.00069	13.240	0.000	5.90%	0.000	1.43%	0.74%
Section 5-7	0.09071	0.05779	13.339	0.09246	0.06329	13.240	-0.002	-1.93%	-0.006	-9.52%	0.74%
Section 7-8	0.02745	0.01768	13.584	0.02733	0.02060	13.540	0.000	0.44%	-0.003	-16.52%	0.32%
Section 8-9	0.02249	0.01473	13.584	0.02189	0.01751	13.540	0.001	2.67%	-0.003	-18.87%	0.32%
Section 4-10	0.14896	0.09526	13.343	0.15150	0.08659	13.240	-0.003	-1.71%	0.009	9.10%	0.77%
Section 10-11	0.05527	0.03679	13.340	0.05585	0.03418	13.240	-0.001	-1.05%	0.003	7.09%	0.75%
Section 10-12	0.08379	0.05212	13.340	0.08549	0.04740	13.240	-0.002	-2.03%	0.005	9.06%	0.75%
Section 12 and downstream	0.02398	0.01402	13.338	0.02420	0.01371	13.240	0.000	-0.92%	0.000	2.21%	0.74%

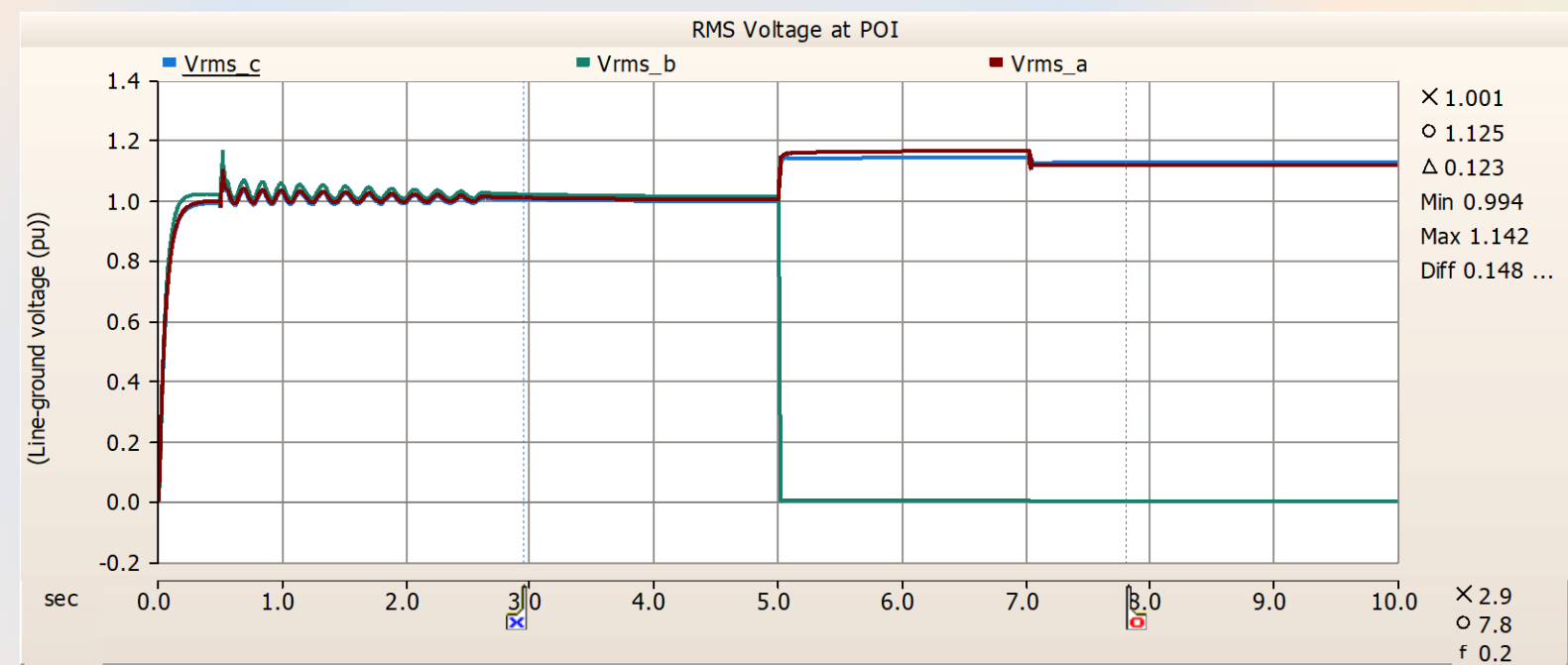
		Short Circuit Values in Amps					
Fault Type		3LG			LG		
Data Source		ASPEN	PSCAD	% Difference	ASPEN	PSCAD	% Difference
Fault Location (V [REDACTED])	Substation Bus Secondary	3057	2910	4.81%	4080	3897	4.49%
	POI [REDACTED]	1343	1321	1.64%	1043	1049	-0.58%

Project Output



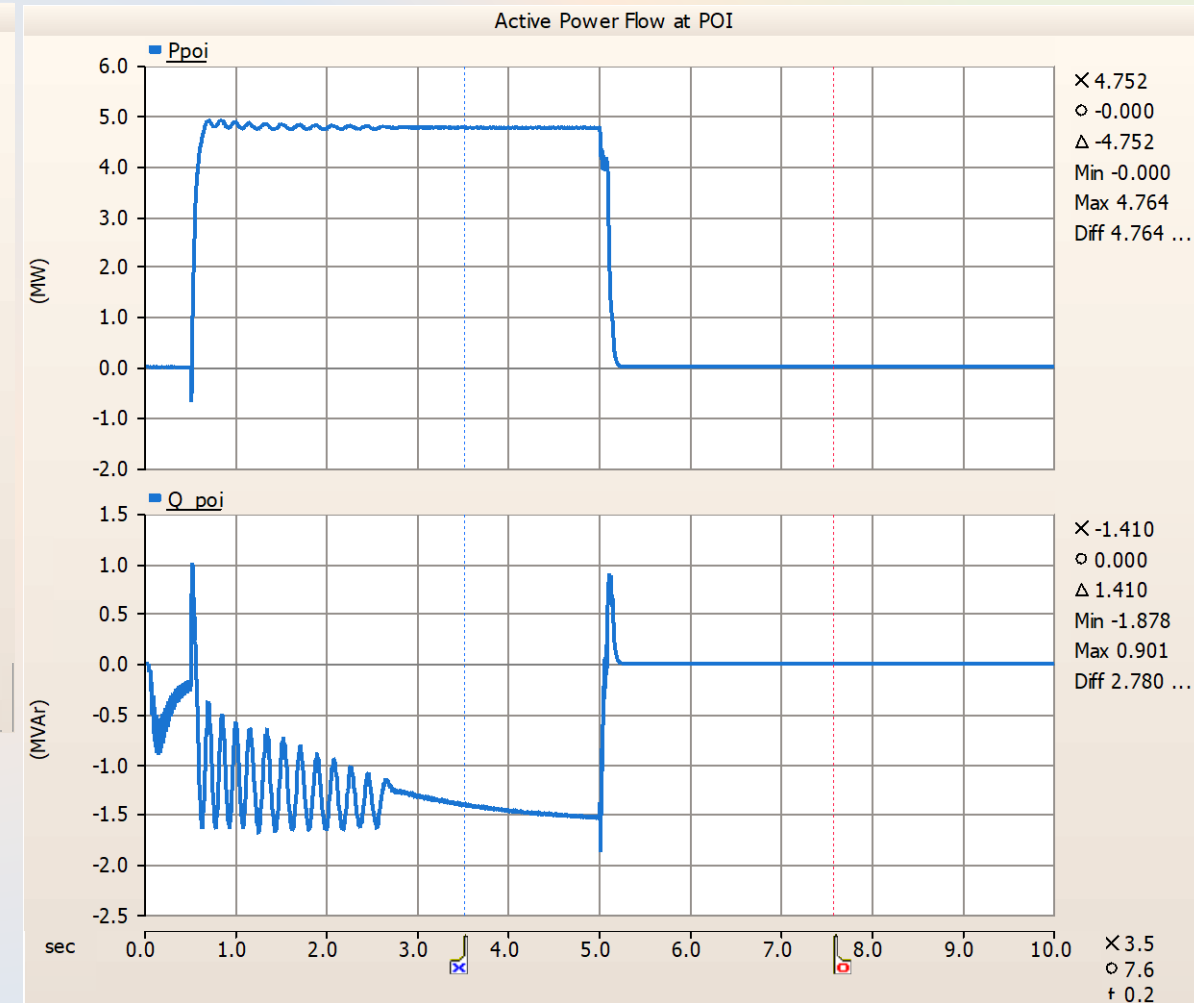
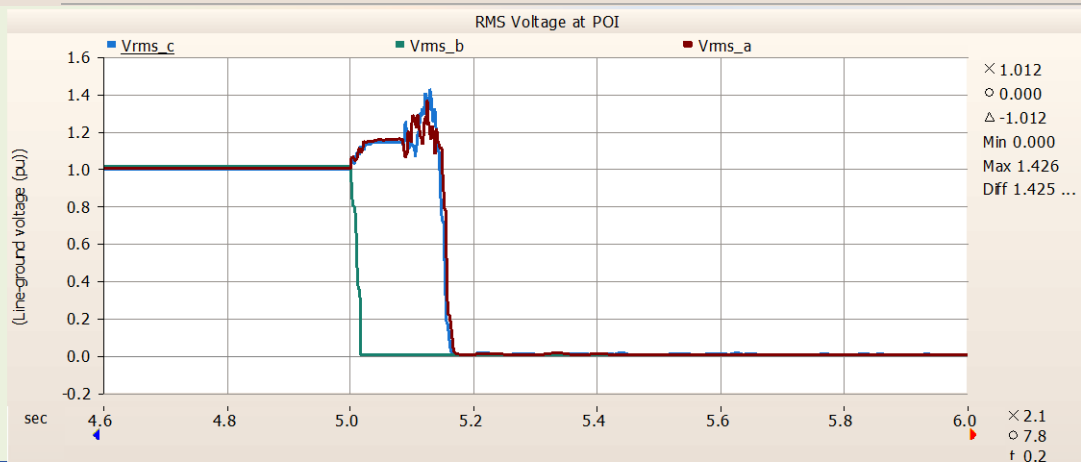
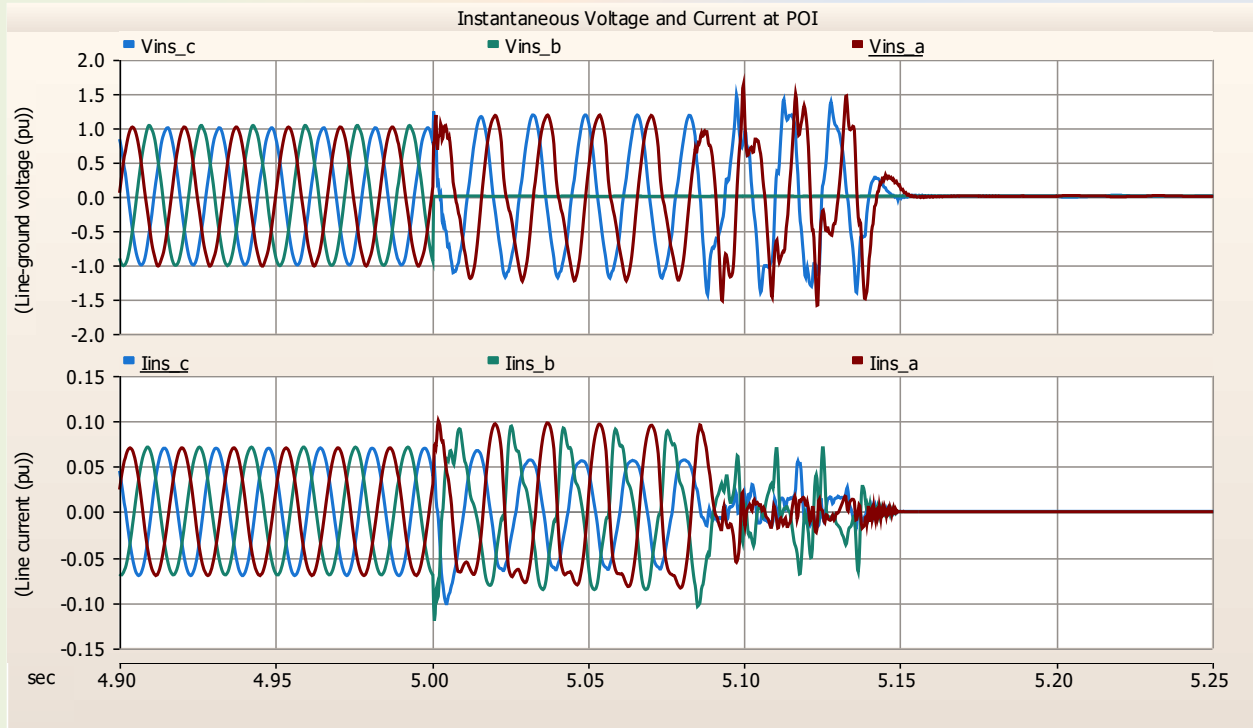
COG calculation

- An L-G fault is applied on Phase B, at the Point of Interconnection (POI) at t= 5 seconds.



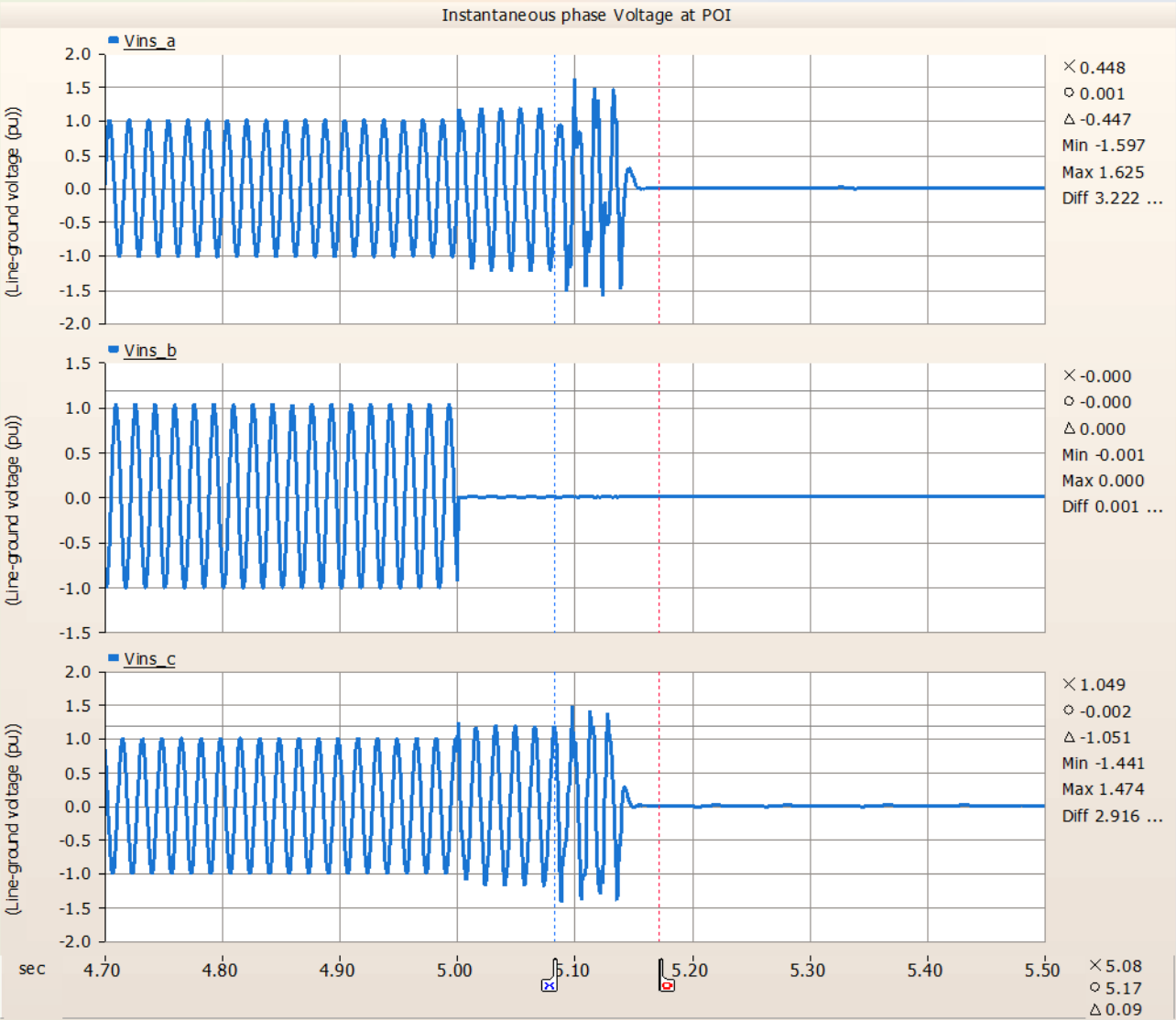
Phases	Unfaulted L-L Voltage (Max)	Faulted L-G Voltage (Max)	COG
Phase A	13.2	8.873	0.672
Phase C	13.2	8.706	0.659

GFOV analysis



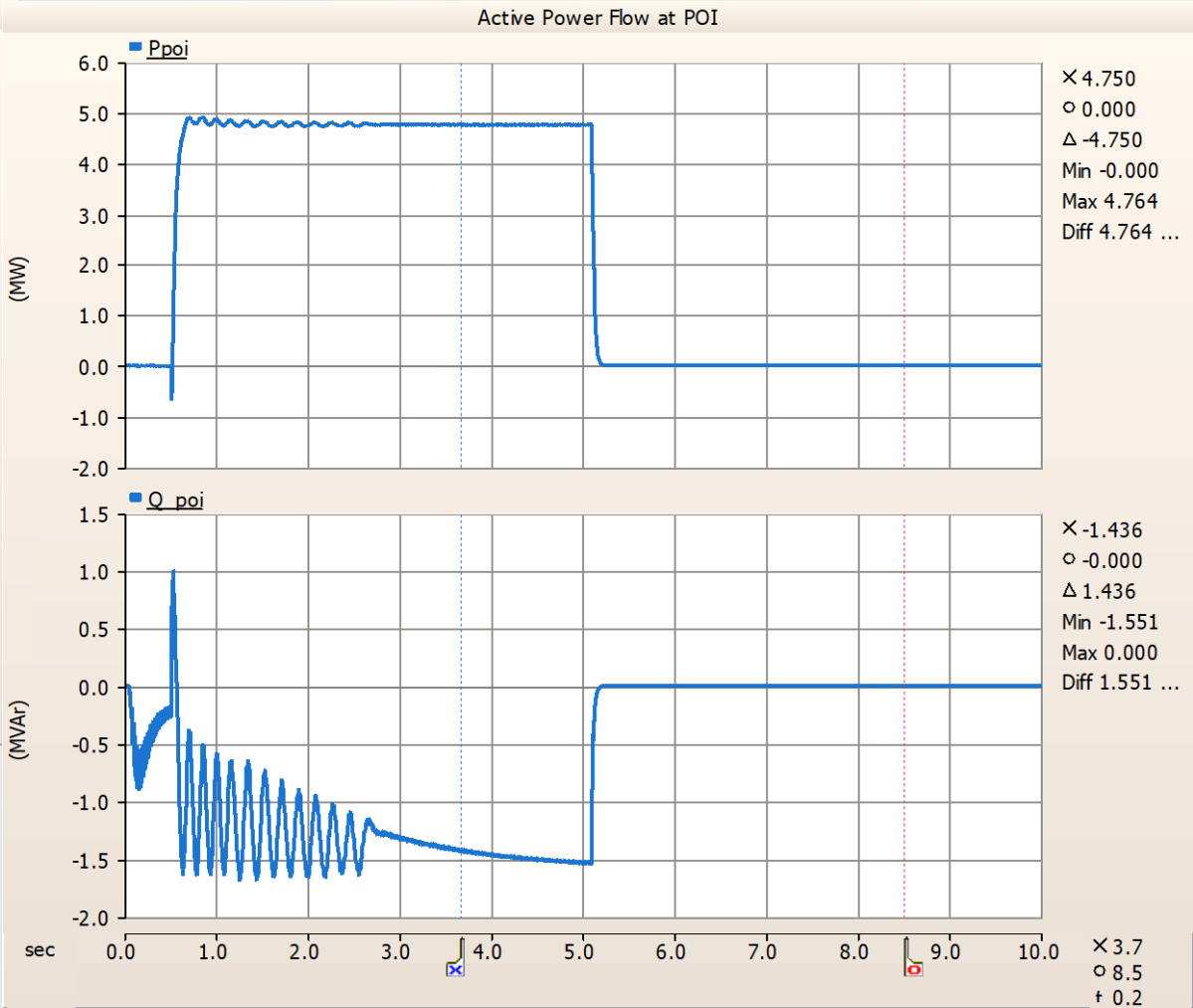
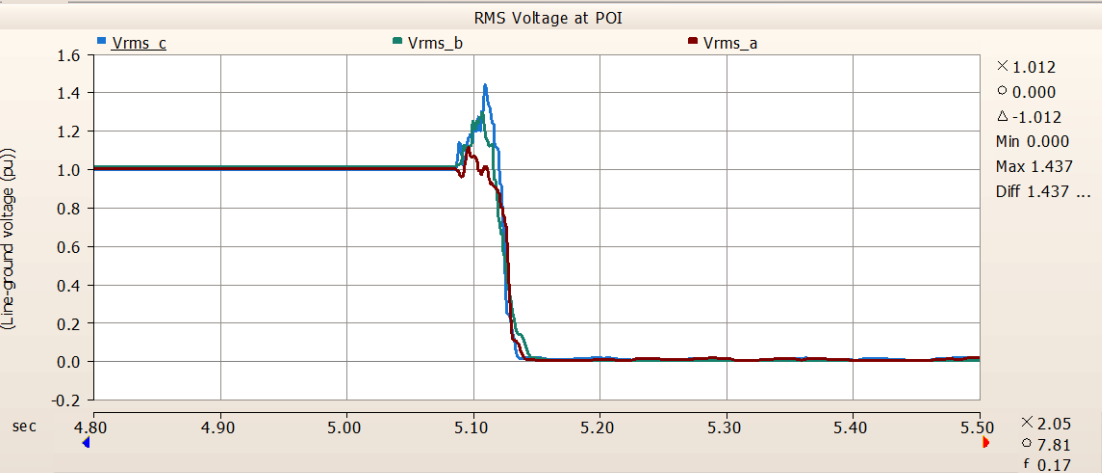
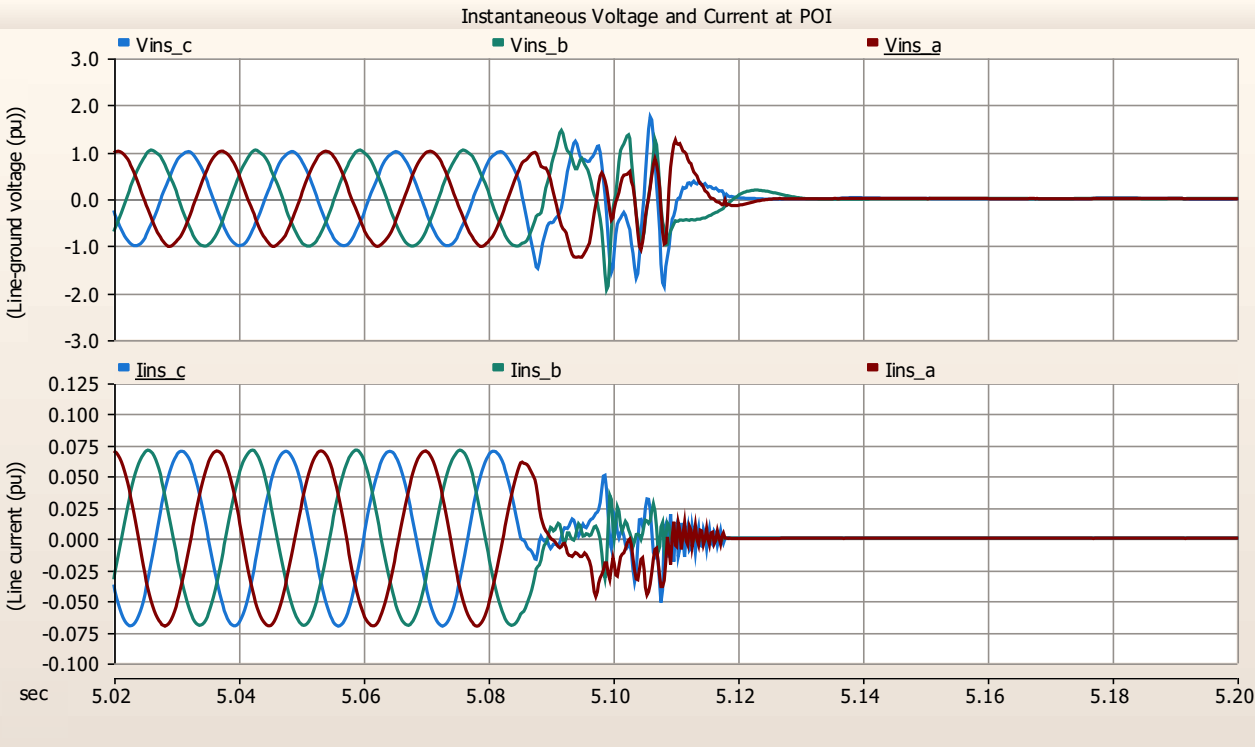
Inverter Trip Time : 0.3 sec

GFOV analysis



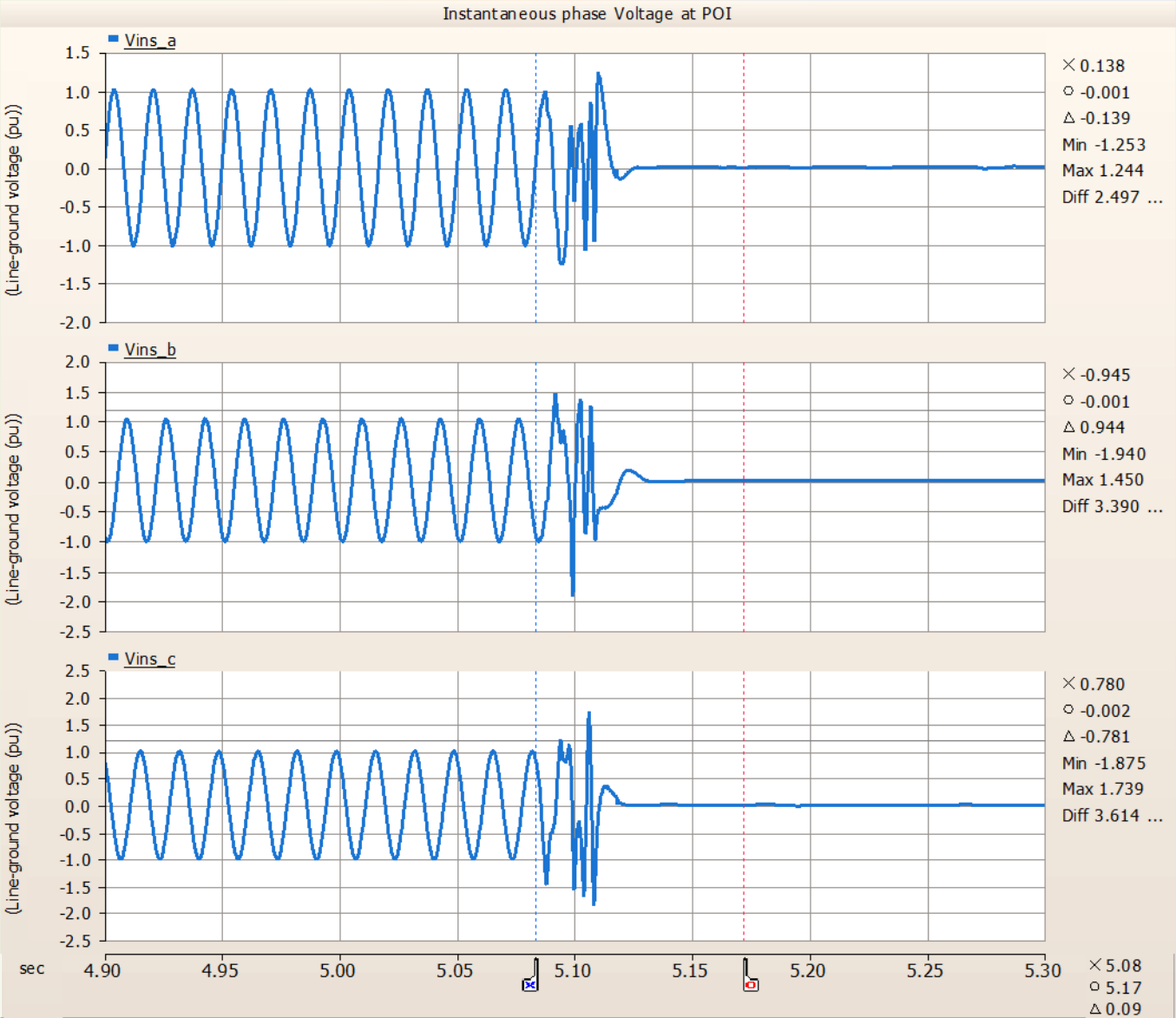
POI Voltage Analysis			
Voltage (pu)	Time (Millisecond)		
	IEEE 1547 - 2018 Guidelines	Phase A	Phase C
1.2 pu	166	8.501	7.483
1.3 pu	16	6.239	4.576
1.4 pu	3	4.119	1.181
1.7 pu	1.6	0.000	0.000
2.0 pu	0	0.000	0.000

LROV analysis



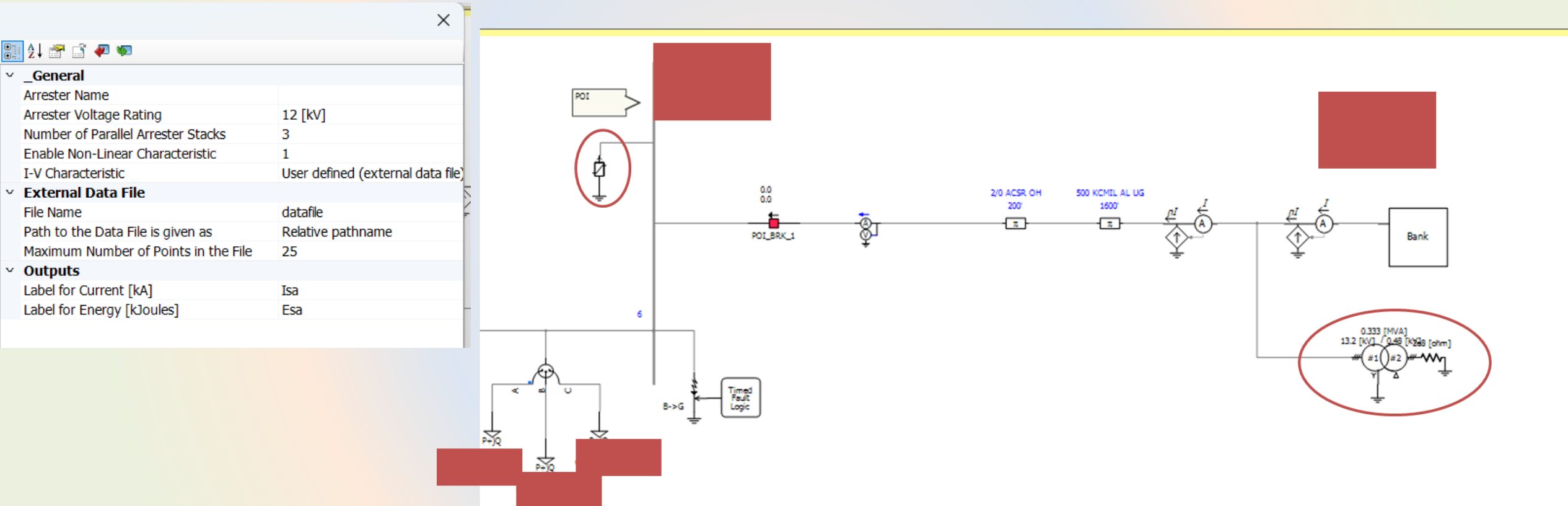
Inverter Trip Time : 0.2 sec

LROV analysis



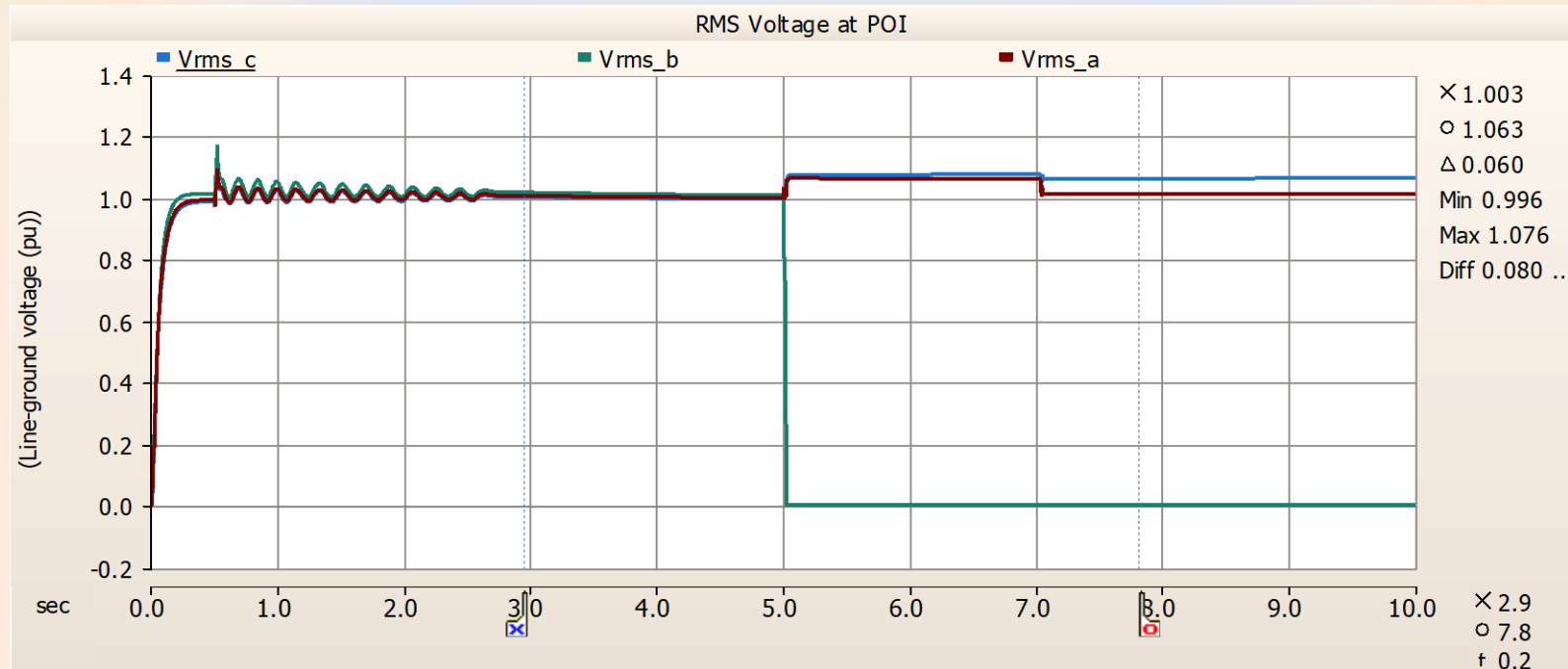
POI Voltage Analysis				
Voltage (pu)	Time (Millisecond)			
	IEEE 1547 - 2018 Guidelines	Phase A	Phase B	Phase C
1.2 pu	166	1.757	3.252	5.163
1.3 pu	16	0.000	2.260	4.143
1.4 pu	3	0.000	1.236	3.229
1.7 pu	1.6	0.000	0.499	0.606
2.0 pu	0	0.000	0.000	0.000

333KVA GND transformer at primary side of GSU and Surge Arrester at POI



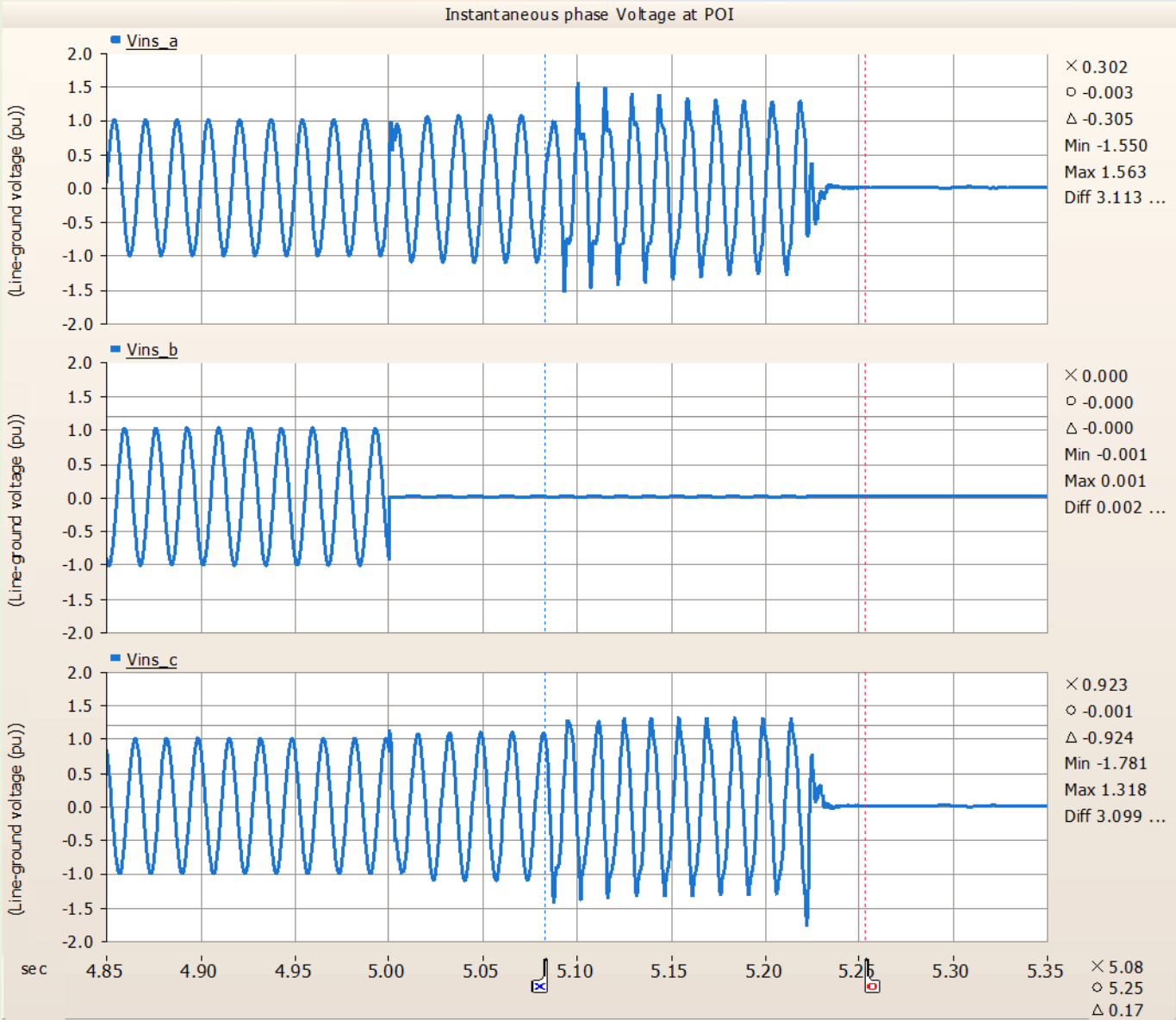
COG with mitigation

- An L-G fault is applied on Phase B, at the Point of Interconnection (POI) at t= 5 seconds.



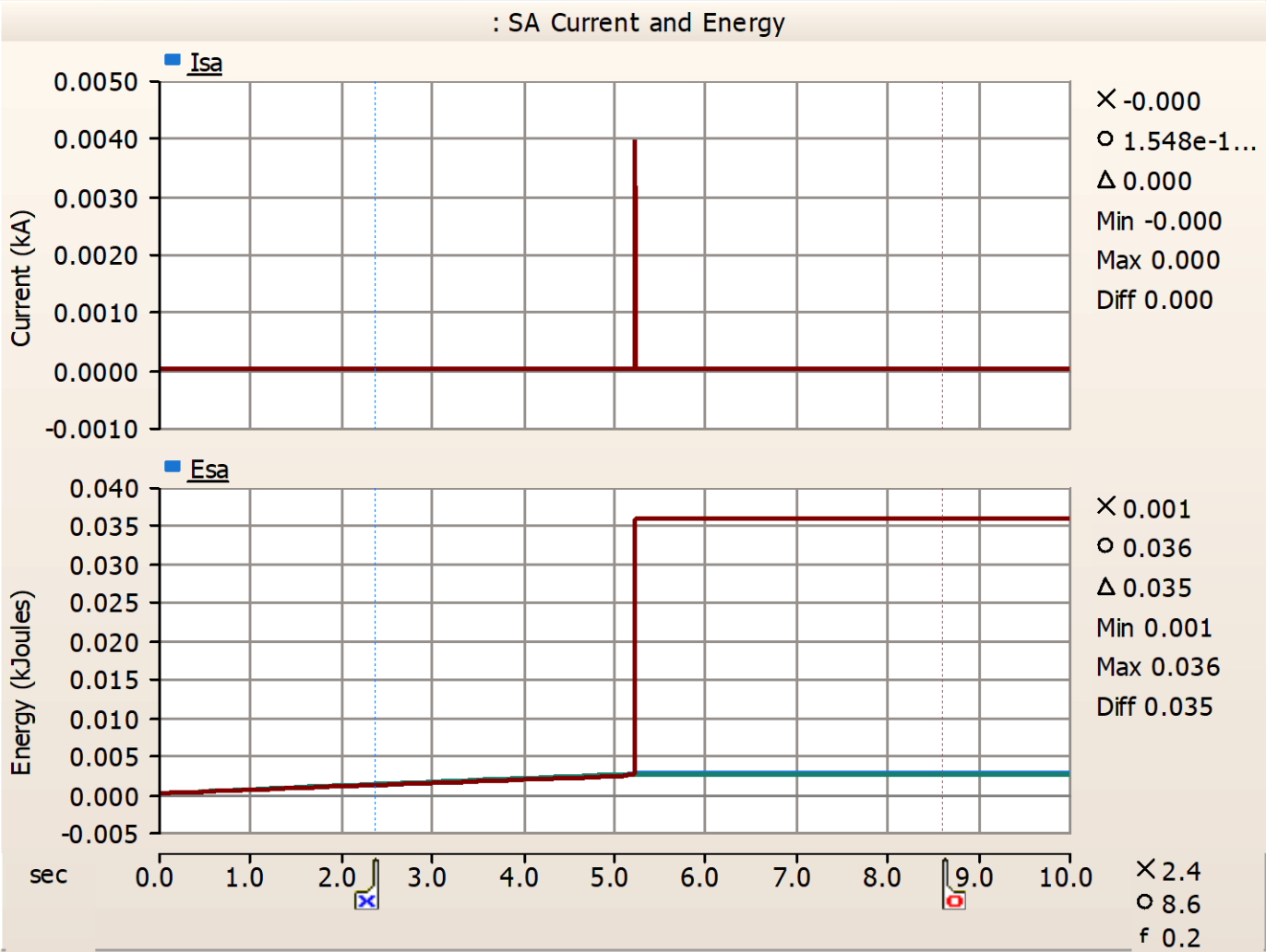
Phases	Unfaulted L-L Voltage (Max)	Faulted L-G Voltage (Max)	COG
Phase A	13.2	8.119	0.615
Phase C	13.2	8.204	0.622

GFOV with mitigation

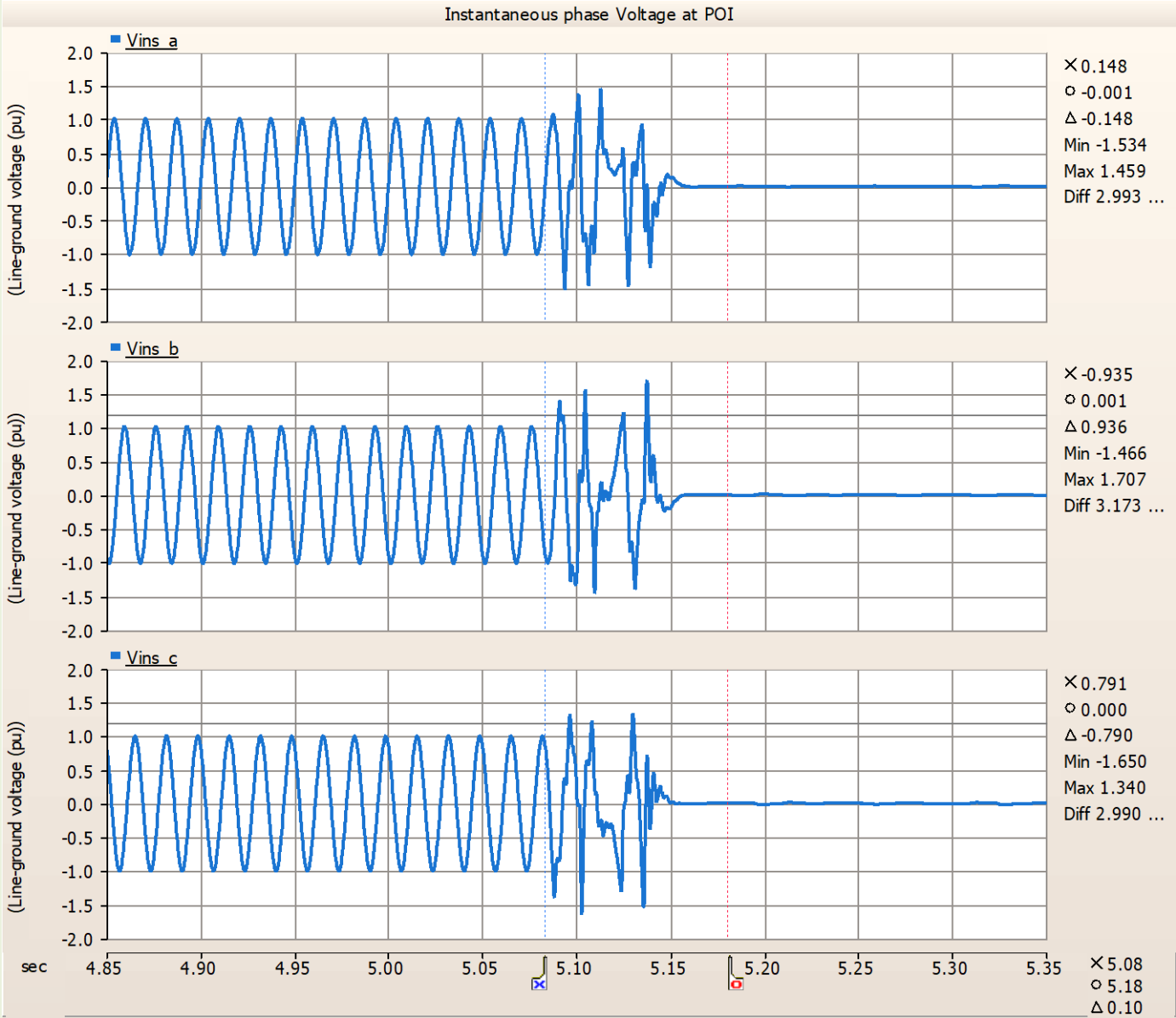


POI Voltage Analysis			
Voltage (pu)	Time (Millisecond)		
	IEEE 1547 - 2018 Guidelines	Phase A	Phase C
1.2 pu	166	19.132	21.175
1.3 pu	16	7.712	8.034
1.4 pu	3	2.701	1.680
1.7 pu	1.6	0.000	0.445
2.0 pu	0	0.000	0.000

Energy Observed by SA

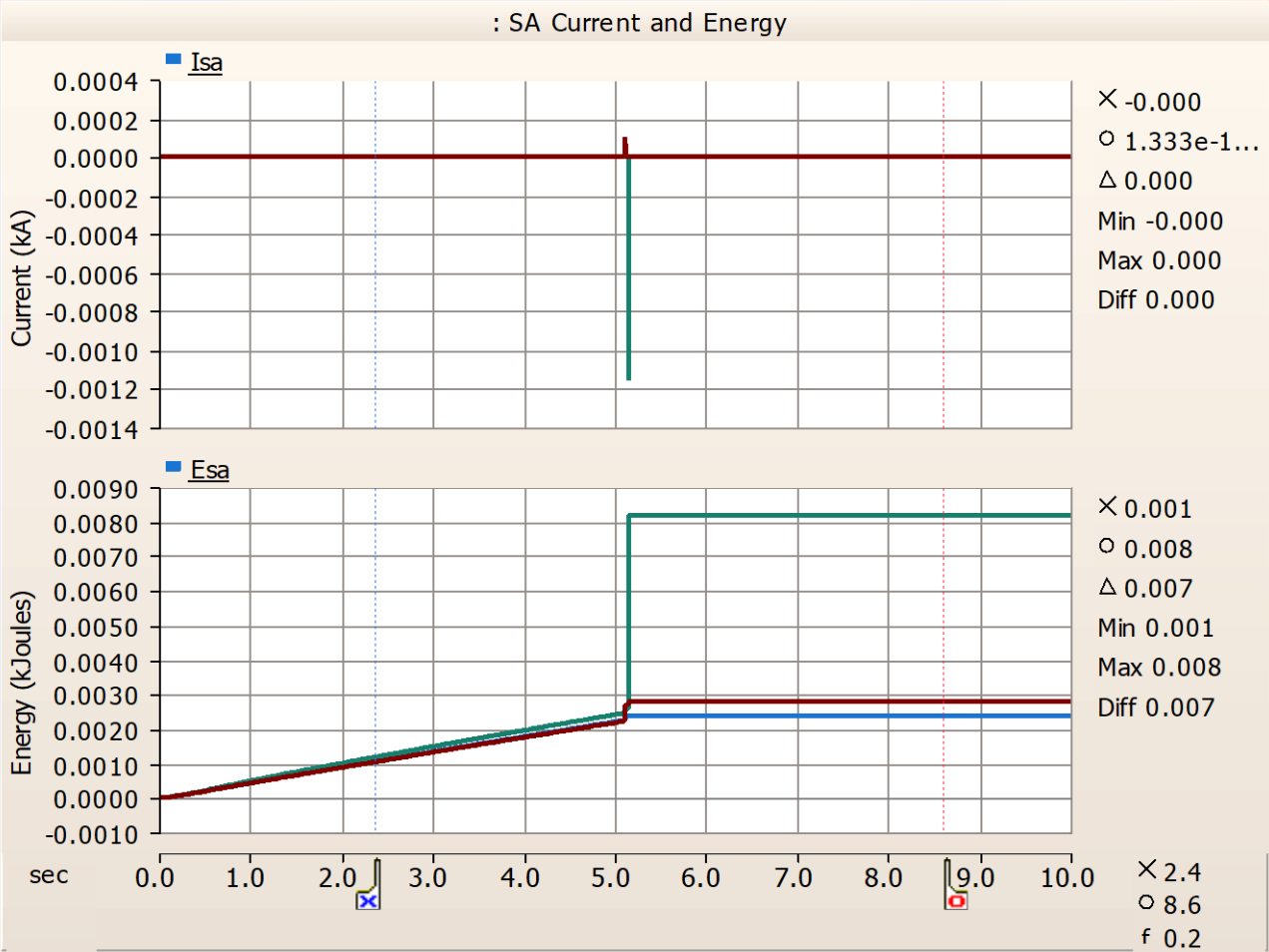


LROV with mitigation



POI Voltage Analysis				
Voltage (pu)	Time (Millisecond)			
	IEEE 1547 - 2018 Guidelines	Phase A	Phase B	Phase C
1.2 pu	166	4.776	7.294	5.937
1.3 pu	16	3.528	4.508	3.331
1.4 pu	3	1.876	2.020	1.491
1.7 pu	1.6	0.000	0.041	0.000
2.0 pu	0	0.000	0.000	0.000

Energy observed by SA



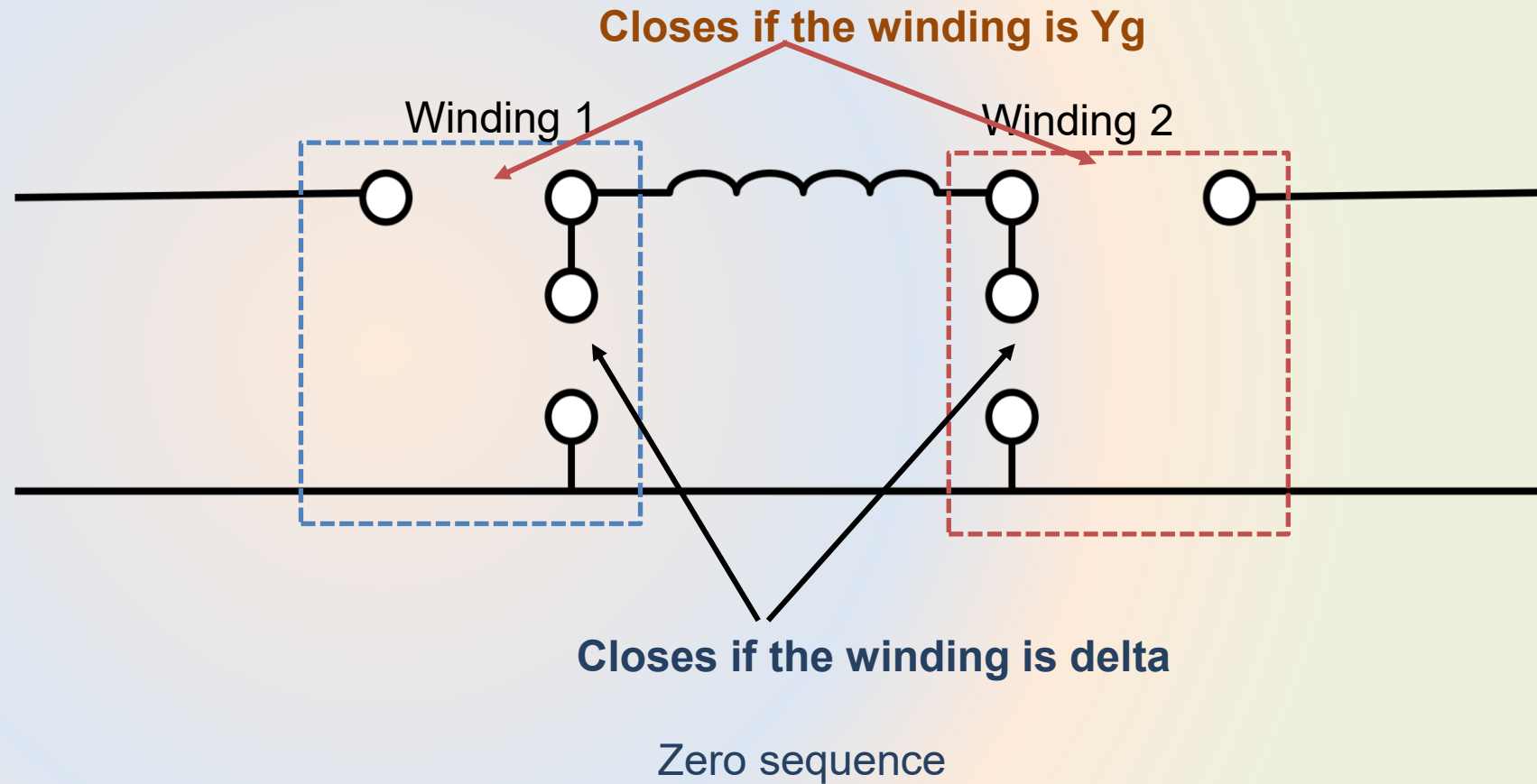
Sequence diagram of Transformer



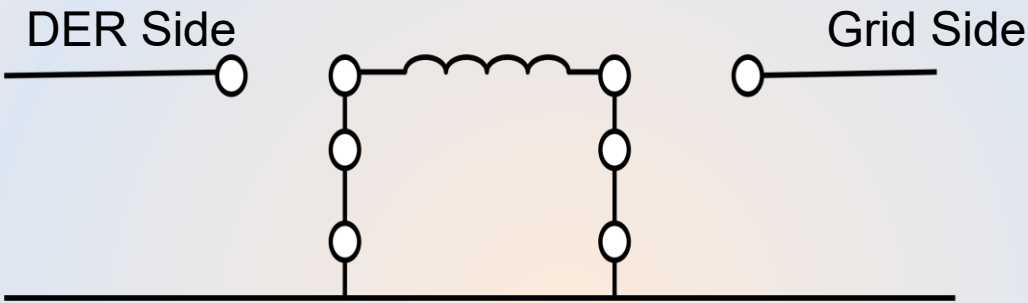
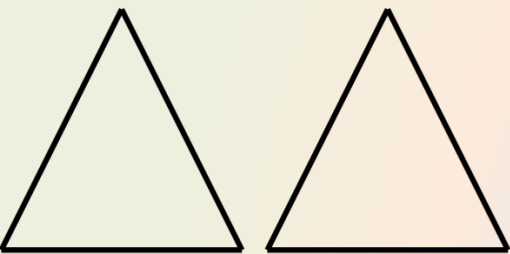
+ve sequence



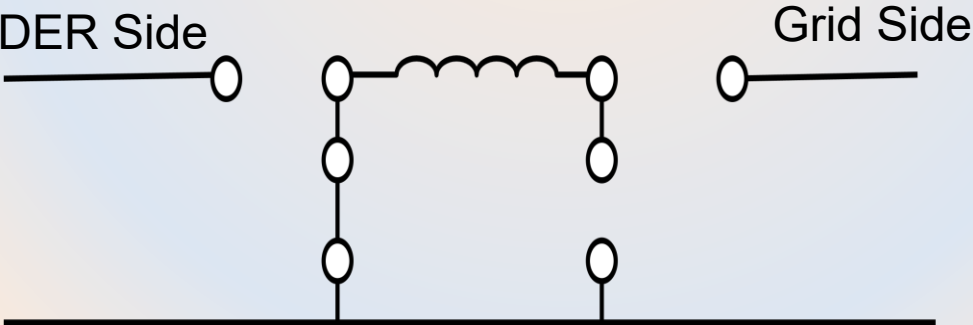
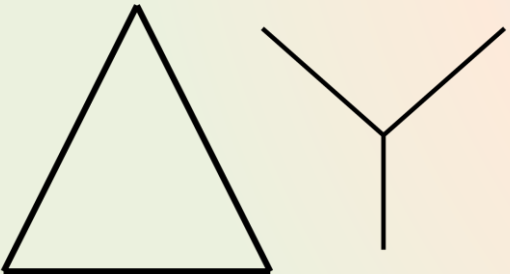
-ve sequence



Delta – Delta and Delta-Y

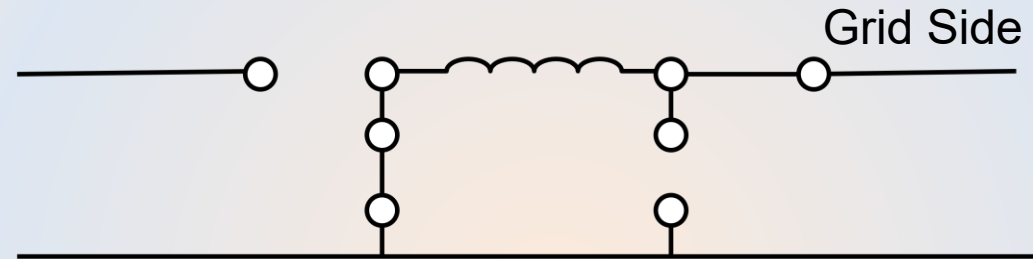
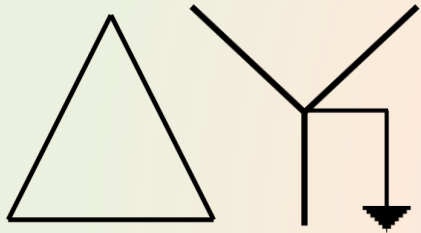


Ungrounded
No zero sequence continuity

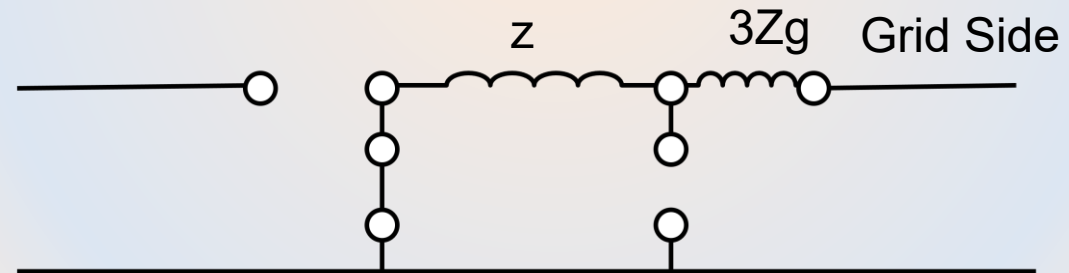
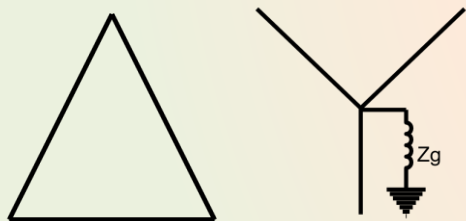


Ungrounded
No zero sequence continuity

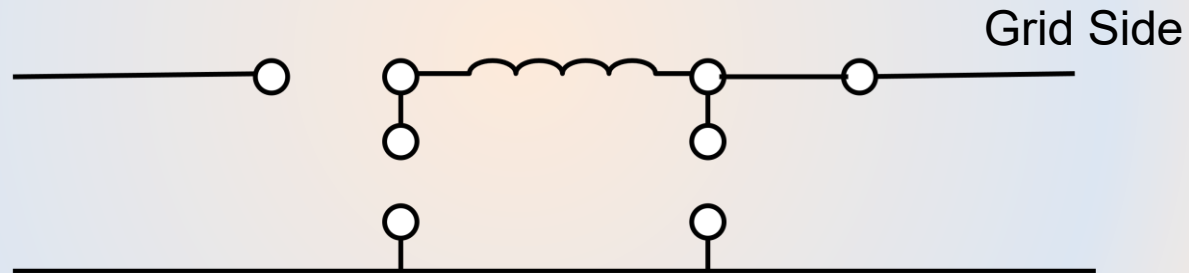
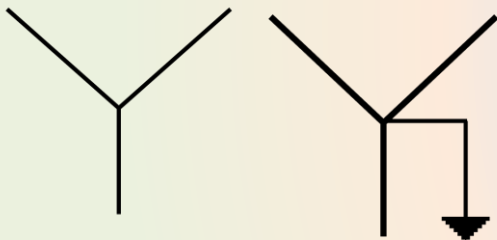
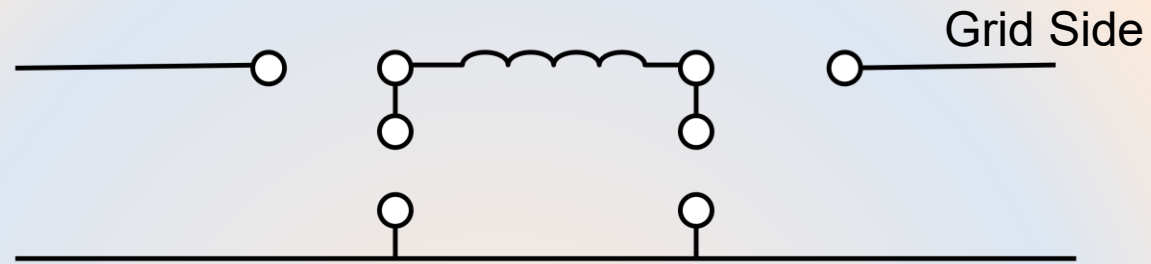
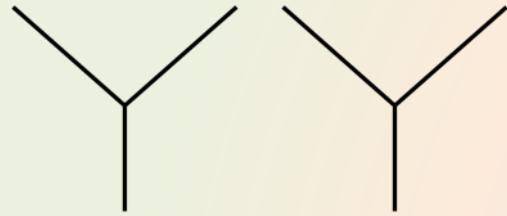
Delta – Yg transformer



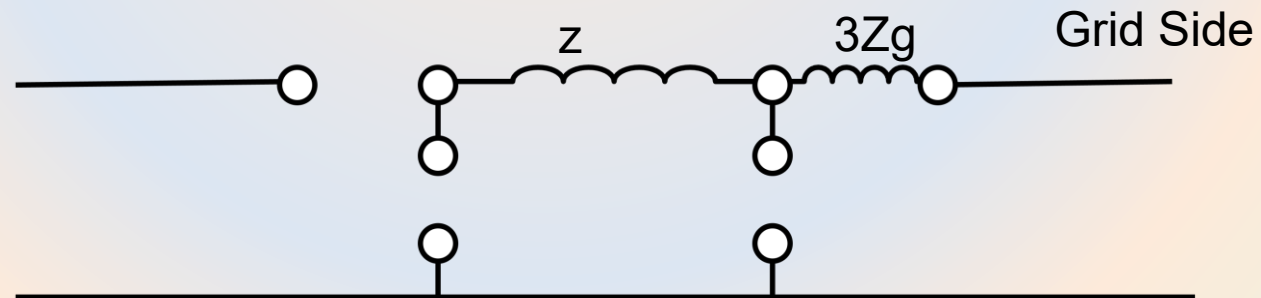
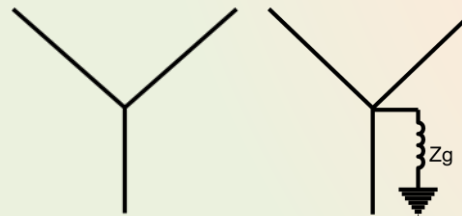
Grounded
Zero sequence continuity



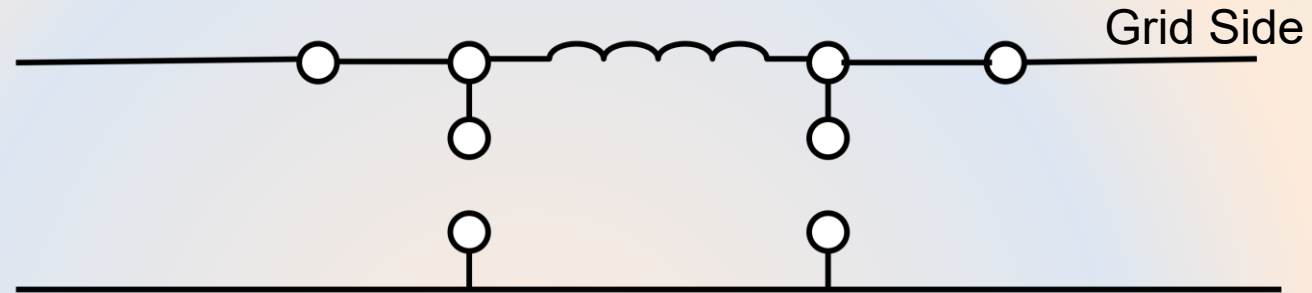
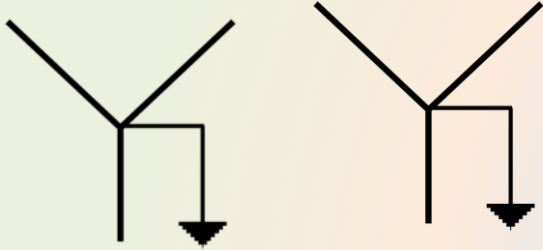
Y-Y/Y-Yg transformer



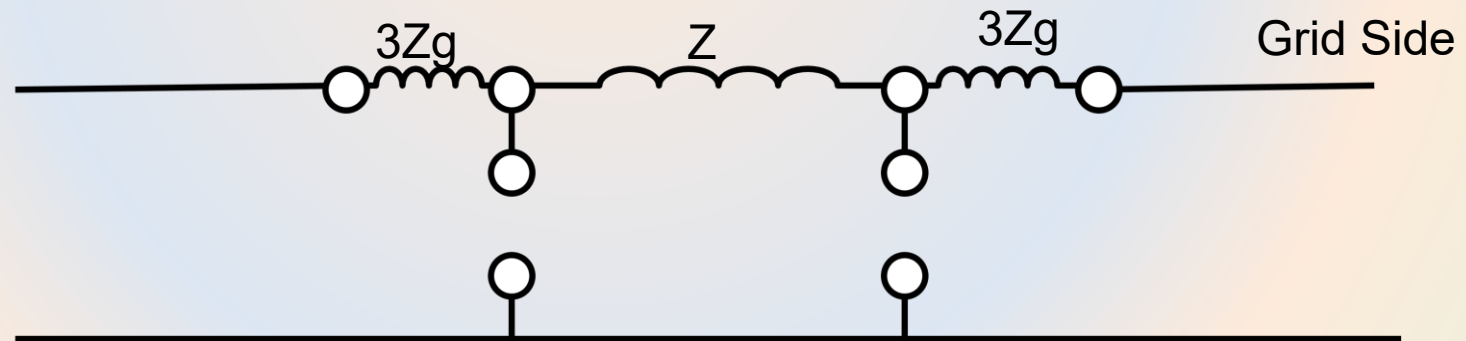
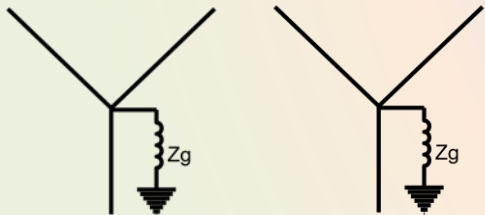
Not Grounded
No Zero sequence
continuity



Yg-Yg transformer



Not a ground source by itself, however it could pass thru a ground source



Desensitization

For a remote bolted SLG fault, the ground fault contribution needs to be within acceptable limit. Some utilities prefer 70-80 amps.

If its higher, it can cause desensitization of upstream device.

