The Evaluation and Mitigation of Ground Fault Over-Voltage from DER-Powered Circuit

ENERGY DELIVERY AND CUSTOMER SOLUTIONS

Track 1: Wires

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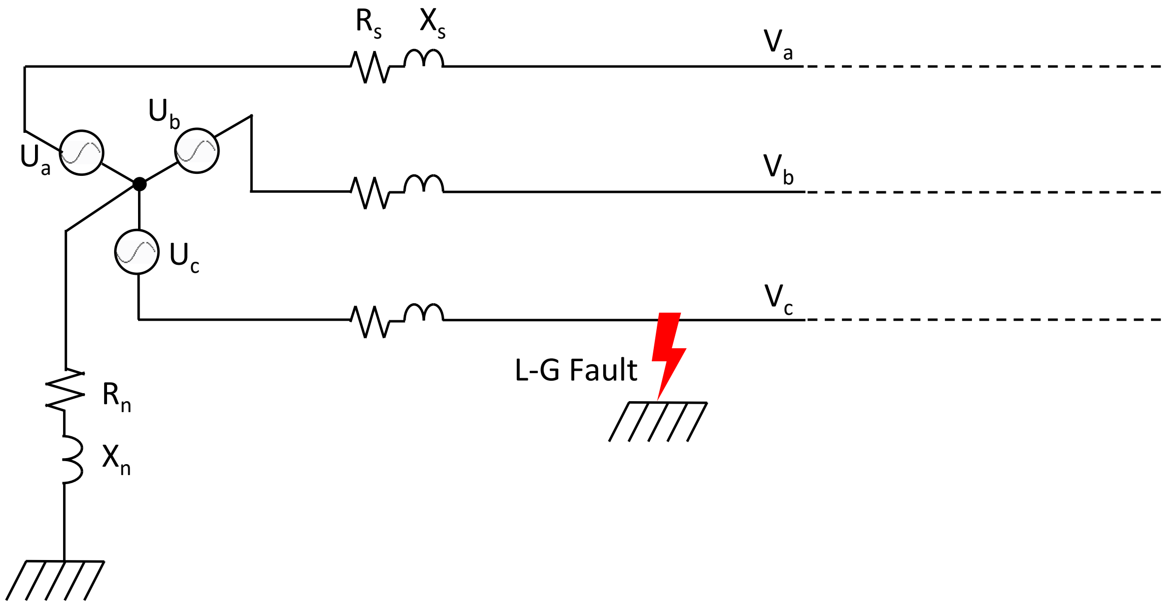
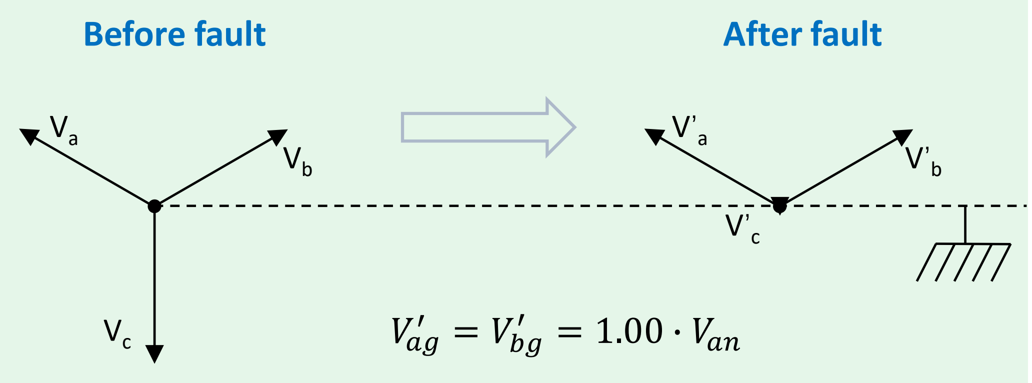
Background and Basics

What is Ground Fault Over Voltage (GFOV)?



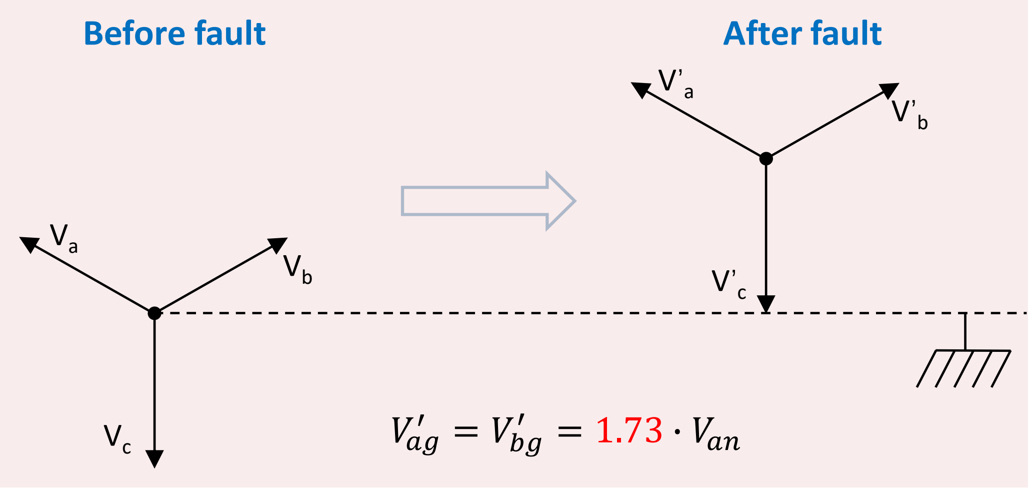
- Circuit powered from a 3-ph voltage source
- Single line to ground (L-G) fault occurs
- Neutral potential shifts away from grounding reference and result in over-voltage in un-faulted phases
- How much the **neutral shifts** is dependent on the **source impedances**

Scenario 1: $Z_n = 0$



$$V'_{ag} = V'_{bg} = 1.00 \cdot V_{an}$$

Scenario 2: $Z_n = \infty$



$$V'_{ag} = V'_{bg} = 1.73 \cdot V_{an}$$

GFOV is caused by neutral shifting

Effective Grounding of Power Systems

- Definition in IEEE Std. C62.92.1
  - "grounded through a sufficiently low impedance such that the coefficient of grounding (**COG**) does not exceed 80%"
  - $COG = \frac{Line-Gnd\ Voltage}{Line-Line\ Voltage} = \frac{E_{LG}}{E_{LL}}$
- For *COG* to be less than 80%, E_{LG} after fault should be less than **138%** of its value before fault
- For classical machines and electric systems, *effective grounding* means the following on the impedances (see Note 1 & 2 below)
  - $\mathbf{R_0 / X_1 < 1}$
  - $\mathbf{X_0 / X_1 < 3}$

Note 1: the derivation of the criteria is based on two assumptions: 1) voltage source is balanced; 2) the source has equal positive sequence and negative sequence impedances
Note 2: grounding can be achieved by connecting the source neutral to ground or utilizing separate grounding banks (e.g., zig-zag transformer)

How is the Impedance Criteria Developed?

- By drawing contours and finding the green square within the 80% COG red curve under various R_1/X_1 ratios

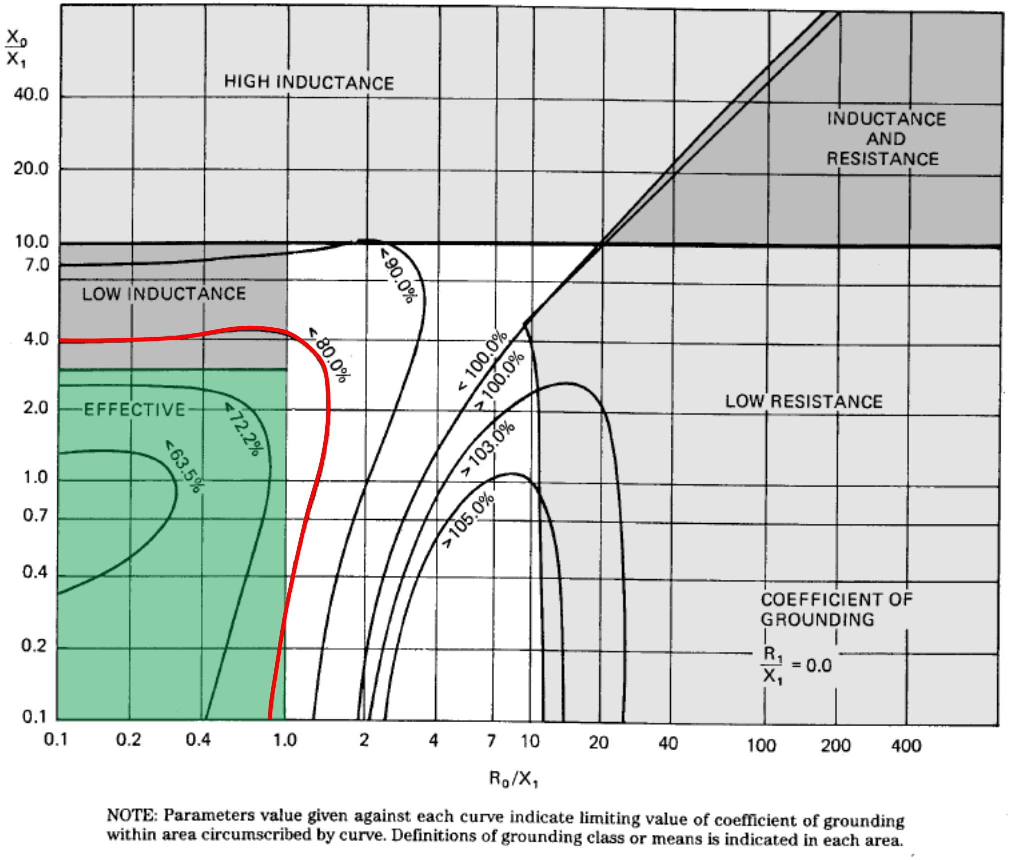


Figure A.2—Boundaries for coefficients of grounding for ratio of positive-sequence resistance R_1 to positive-sequence reactance X_1 of 0

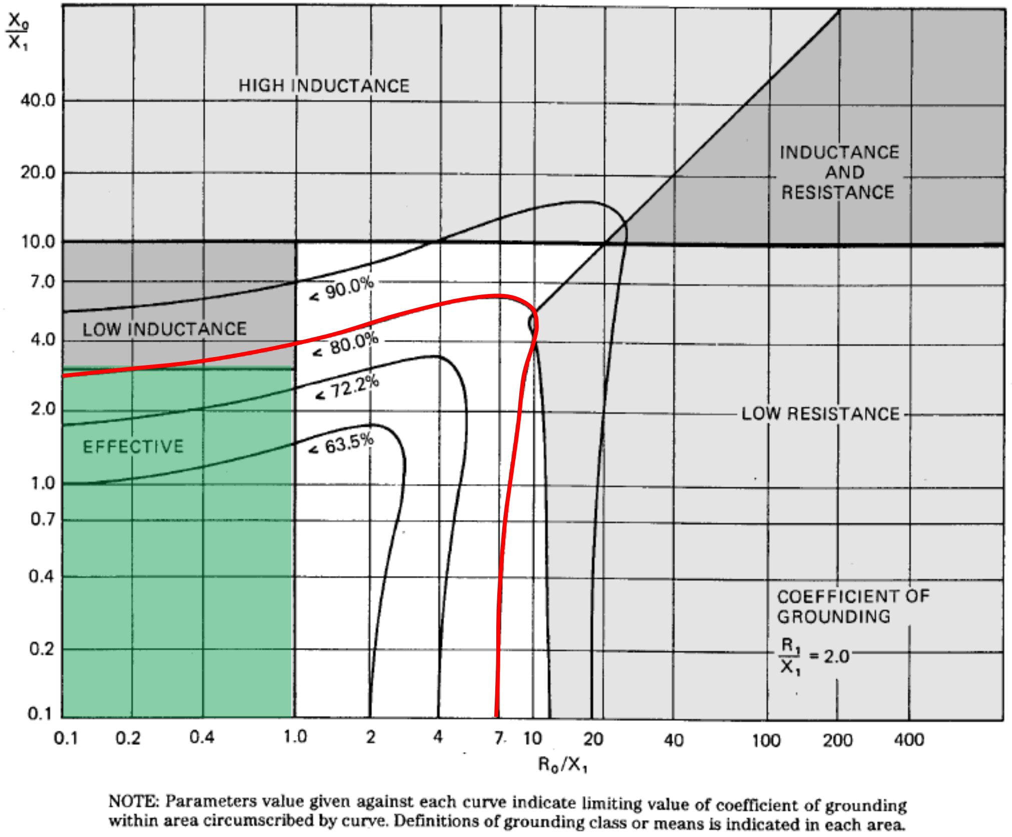
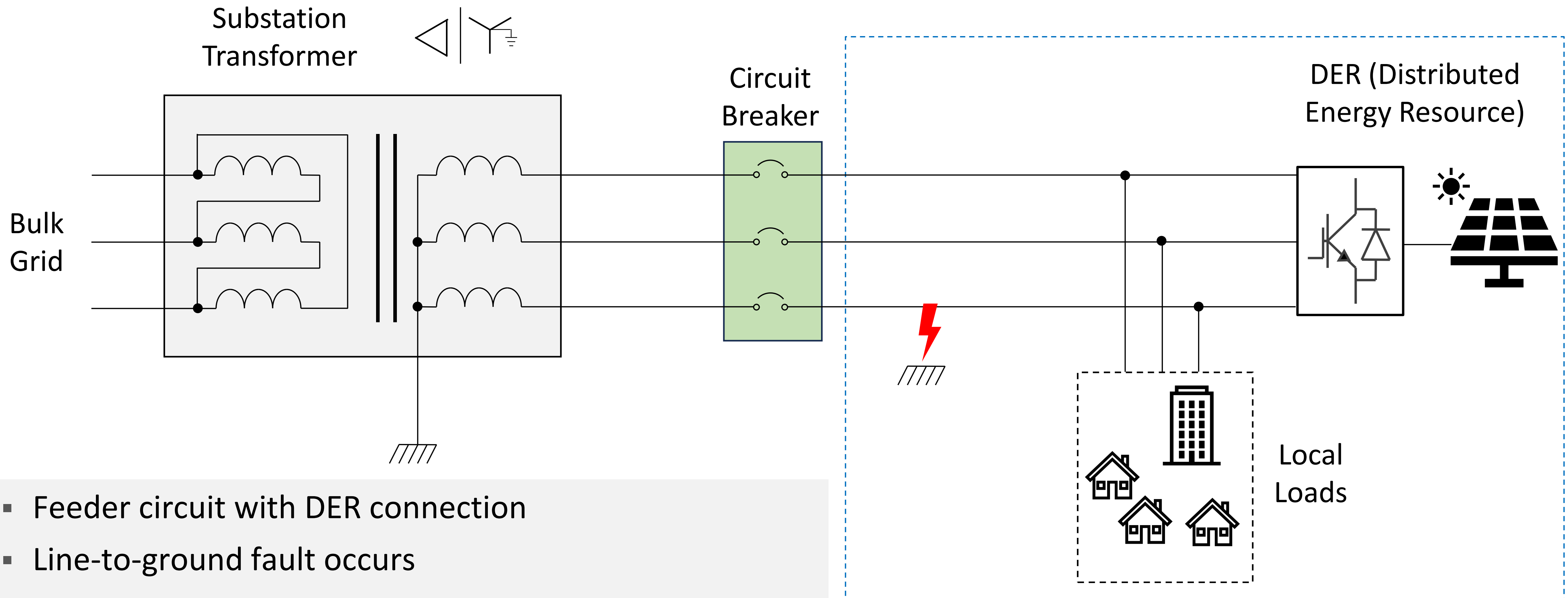


Figure A.6—Boundaries for coefficients of grounding for ratio of positive-sequence resistance R_1 to positive-sequence reactance X_1 of 2.0

Figure source: IEEE Std. C62.92.1

What Happens with DER in Circuit?



- Feeder circuit with DER connection
- Line-to-ground fault occurs
- Main circuit breaker opens and takes away the grounding from substation
- Circuit section remains energized and may experience **GFOV** if not effectively grounded

Circuit section remains energized by the DER before the DER trips or other circuit protection takes place

Why Classical Grounding Practice Fails on Inverter DER?

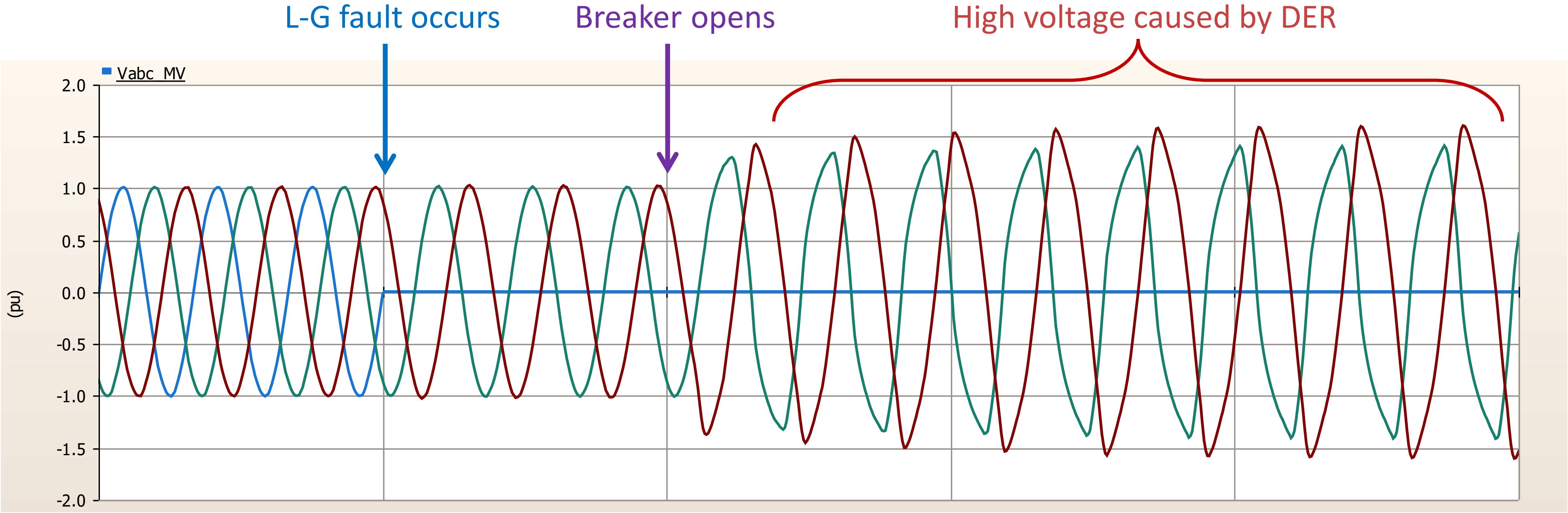
Synchronous generator

- Behaves as a **voltage source**
- Maintain **balanced** operation under fault
- Maintain **sinusoidal** voltage waveform under fault

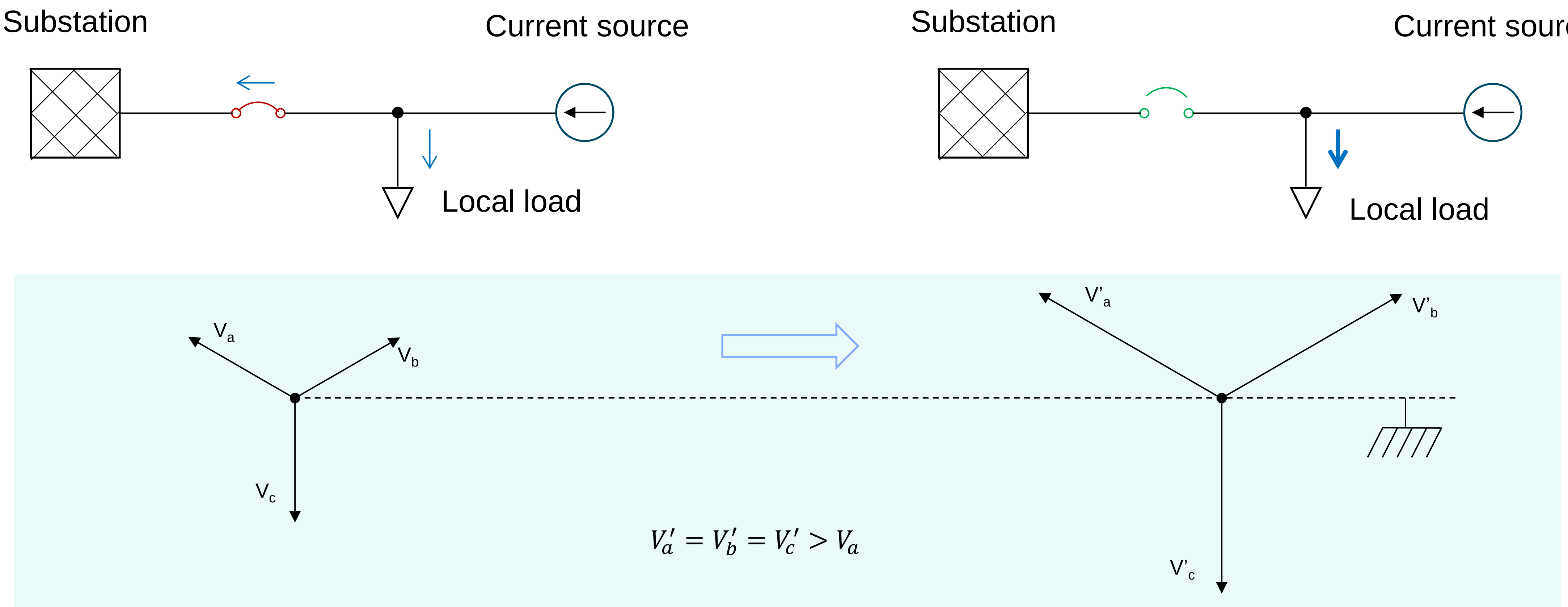
Inverter-based source

- Behaves as a **current source** (fast current regulation)
- May be highly **unbalanced** under fault (with each phase current separately limited)
- Voltage waveform can be **distorted** under fault

Circuit simulation showing the over-voltage caused by an inverter DER during a ground fault



What is Load Rejection Over-Voltage (LROV)?

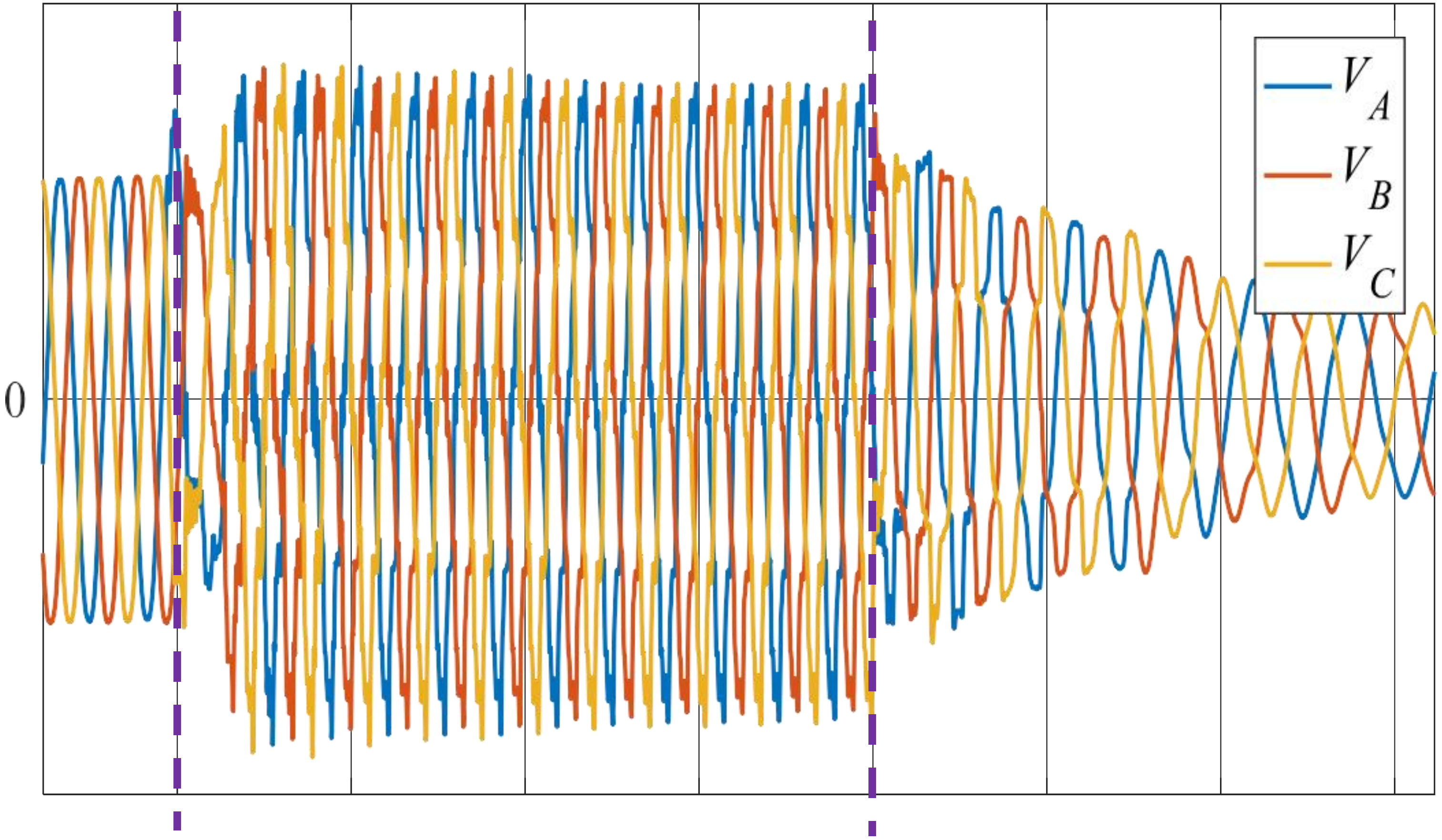


$$V_a' = V_b' = V_c' > V_a$$

LROV happens when higher current goes into impedance load

LROV Event in Real World

Source: Dominion Energy



- A 5MW PV plant connected at 34.5kV
- A blue-sky breaker opening left the PV plant and local loads in **island**
- LROV reached **159%** of the nominal voltage and lasted **12 cycles**
- LROV happens in **balanced** circuit without ground fault
- LROV is **easy to detect** and protect by DER control

In a DER-sourced circuit, LROV and GFOV may happen together

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Screening of Ground Fault Induced TOV

Gen/Load Ratio, Grounded Load, & Inverter Control

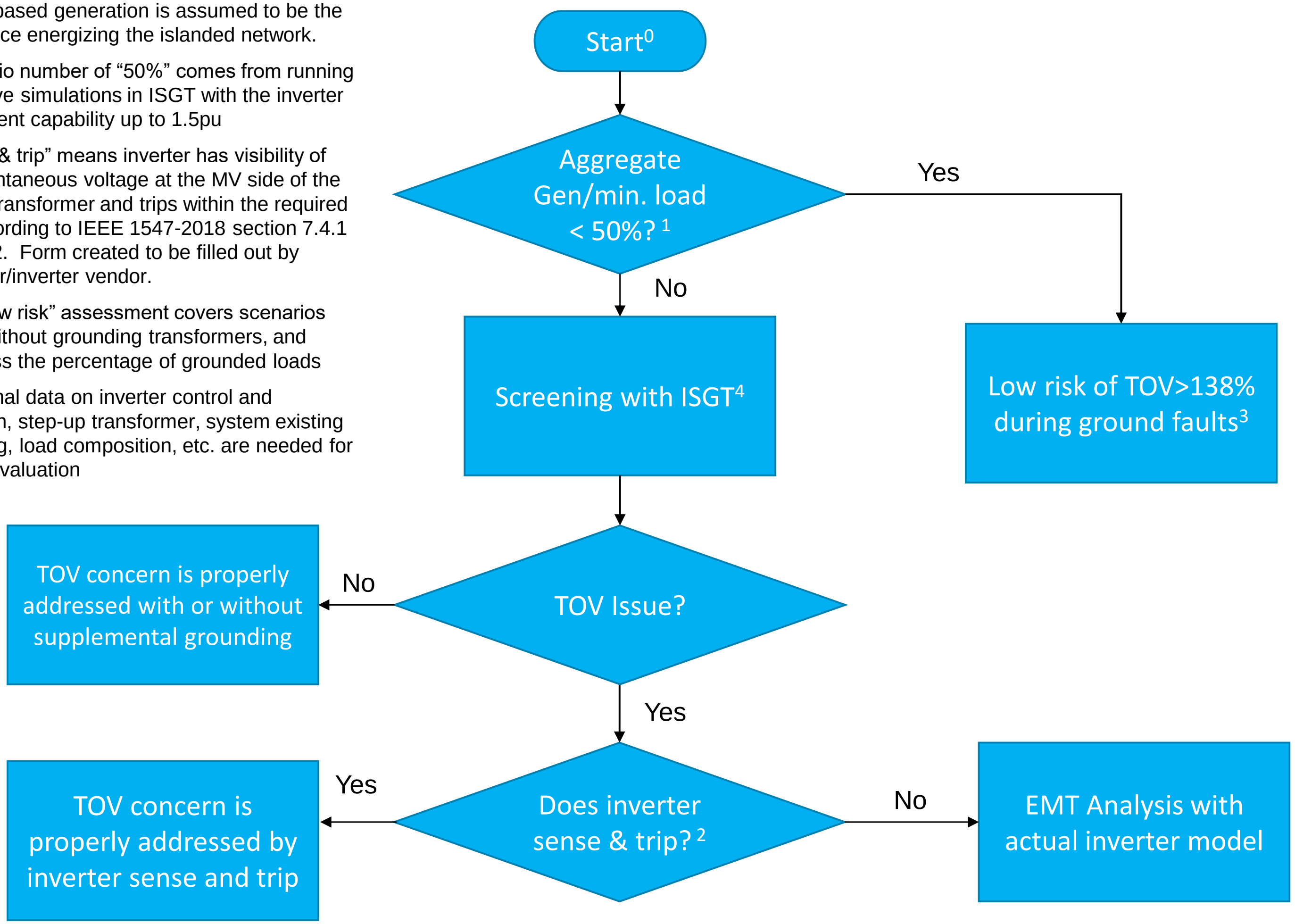
[0] This flow chart evaluates the risk of TOV due to SLG fault with loss of the main grid. 3-phase Inverter-based generation is assumed to be the only source energizing the islanded network.

[1] This ratio number of “50%” comes from running exhaustive simulations in ISGT with the inverter fault current capability up to 1.5pu

[2] “sense & trip” means inverter has visibility of the instantaneous voltage at the MV side of the step-up transformer and trips within the required time according to IEEE 1547-2018 section 7.4.1 and 7.4.2. Form created to be filled out by developer/inverter vendor.

[3] This “low risk” assessment covers scenarios with or without grounding transformers, and regardless the percentage of grounded loads

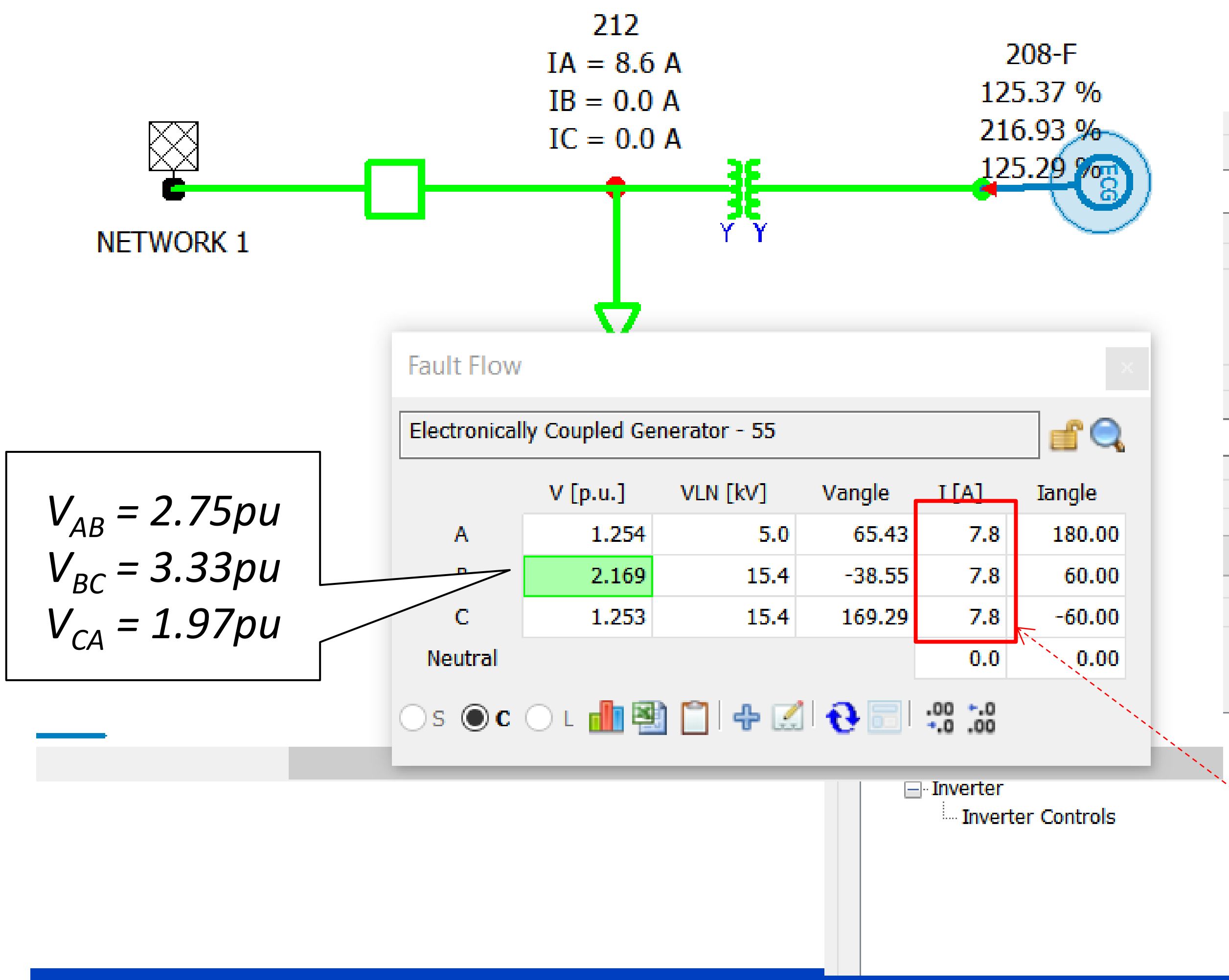
[4] Additional data on inverter control and protection, step-up transformer, system existing grounding, load composition, etc. are needed for reliable evaluation



- An island may not form if
  - Low gen/load ratio (not enough current to sustain voltage)
  - Effective control / protection (e.g., anti-islanding logic) of inverter DER
- Grounded load may render effective grounding (COG<0.8)
  - No additional grounding source required
- Characterizing inverter DER behavior can be challenging, but possible

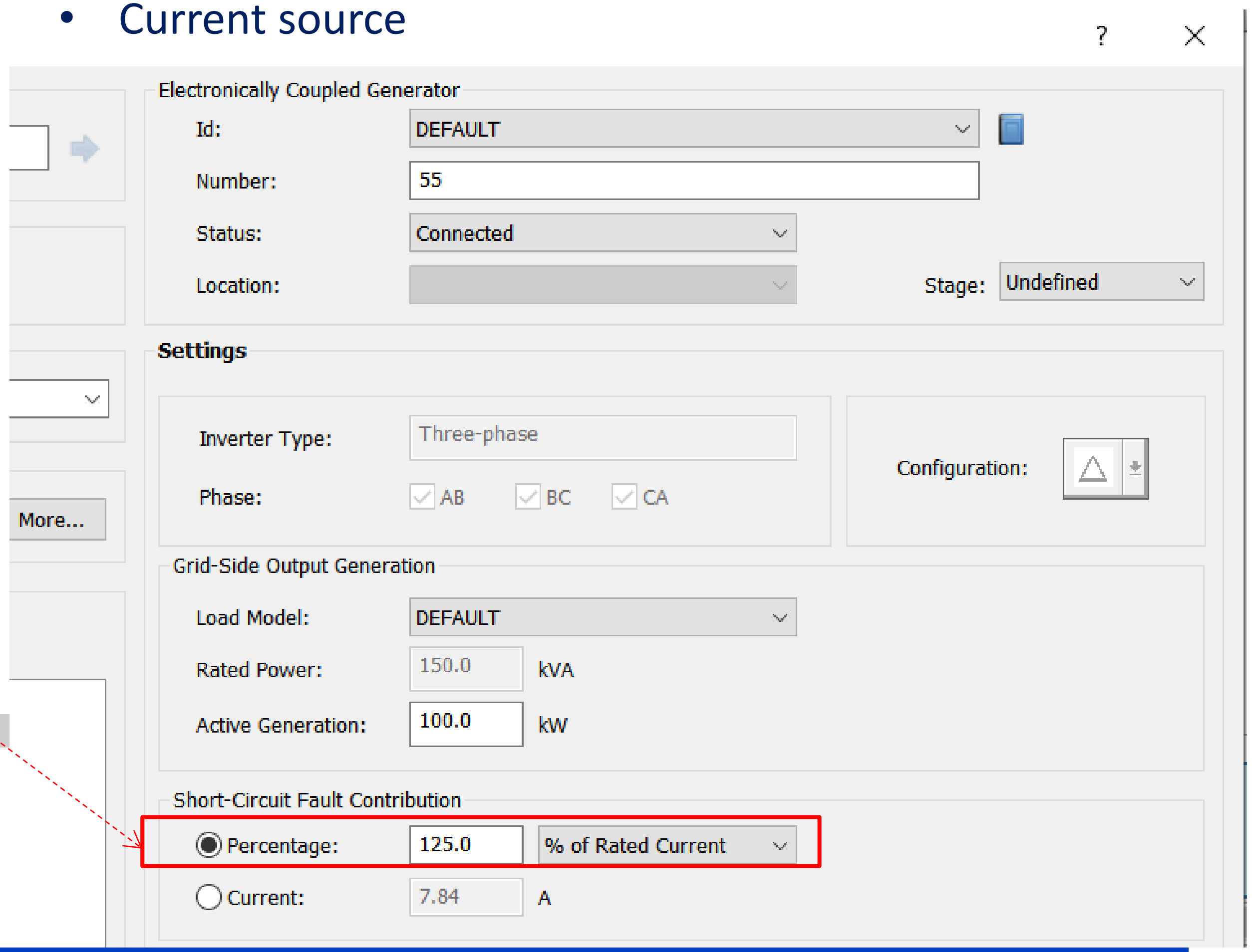
Supplemental grounding can incur significant cost

Limitation in Commercial Software



Two Fault Models of Inverter in CYME

- Voltage behind impedance
- Current source



Inverters are subject to both V and I limits

Inverter-based Supplemental Grounding Tool (ISGT)

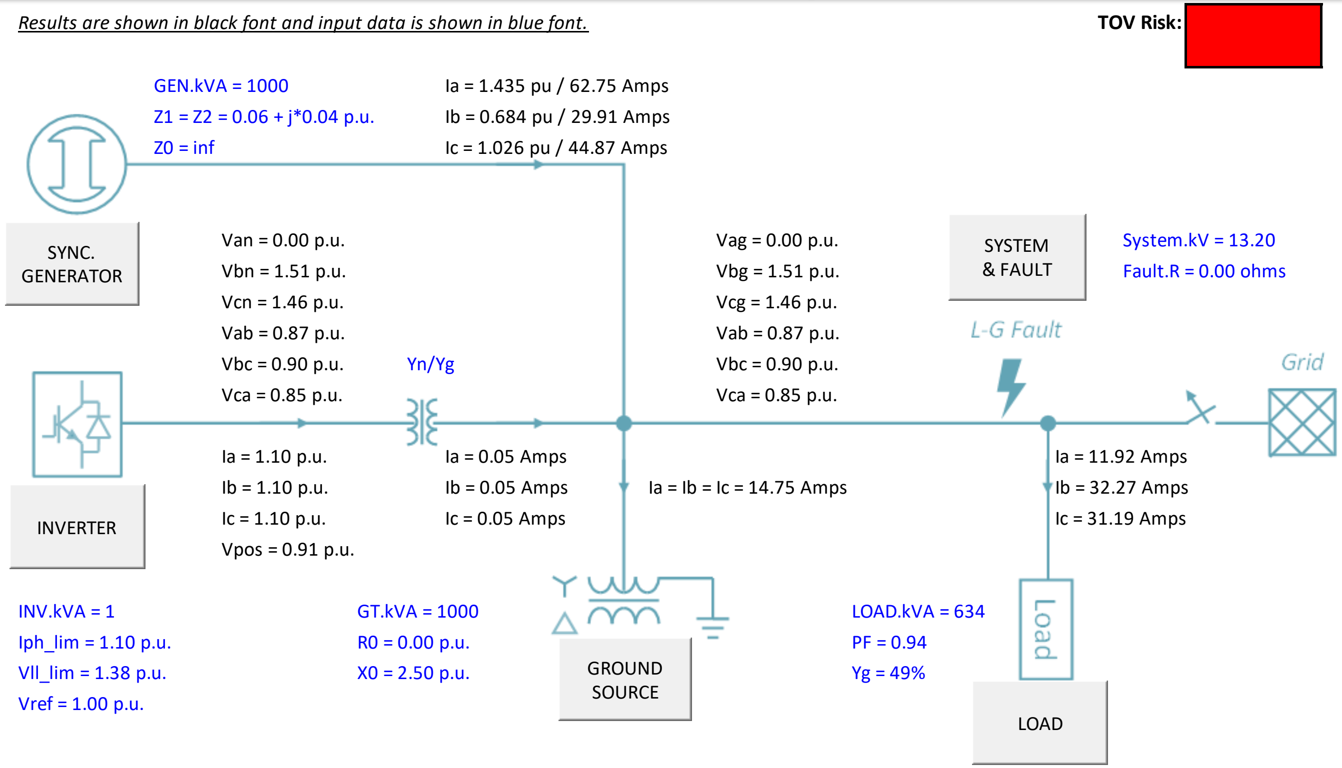
https://www.epri.com/research/products/000000003002028194

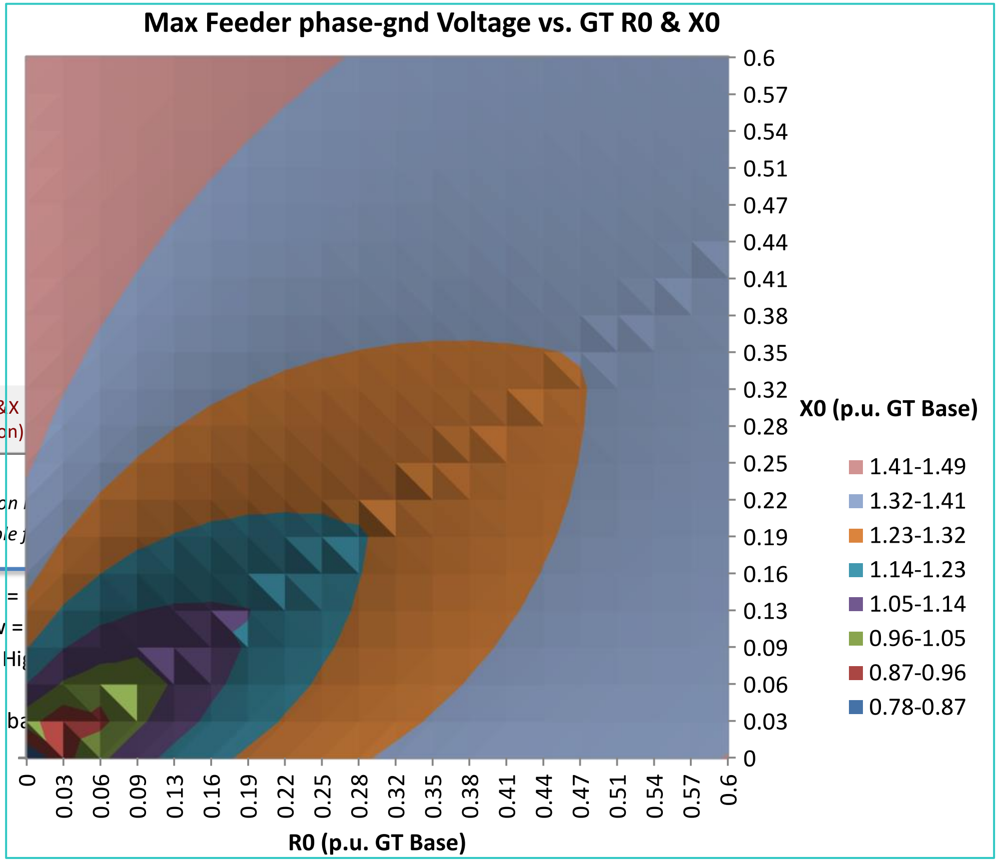
Line to Ground Fault Simulation Result

Max. Feeder Phase-ground Voltage During Fault (pu	1.51 ~ 1.51
OV Flag (>1.38pu per IEEE1547 7.4.1)	LV&MV
Inverter Pout (pu @ Inverter Base)	0.80
Generation to Min. Load Ratio	1.58
kW Loss in GT Neutral Resistor (assuming 4% V0)	0

Calculate Fault | About | Reset Data | Max_V vs. GT_R&X (for GT Zg Selection)

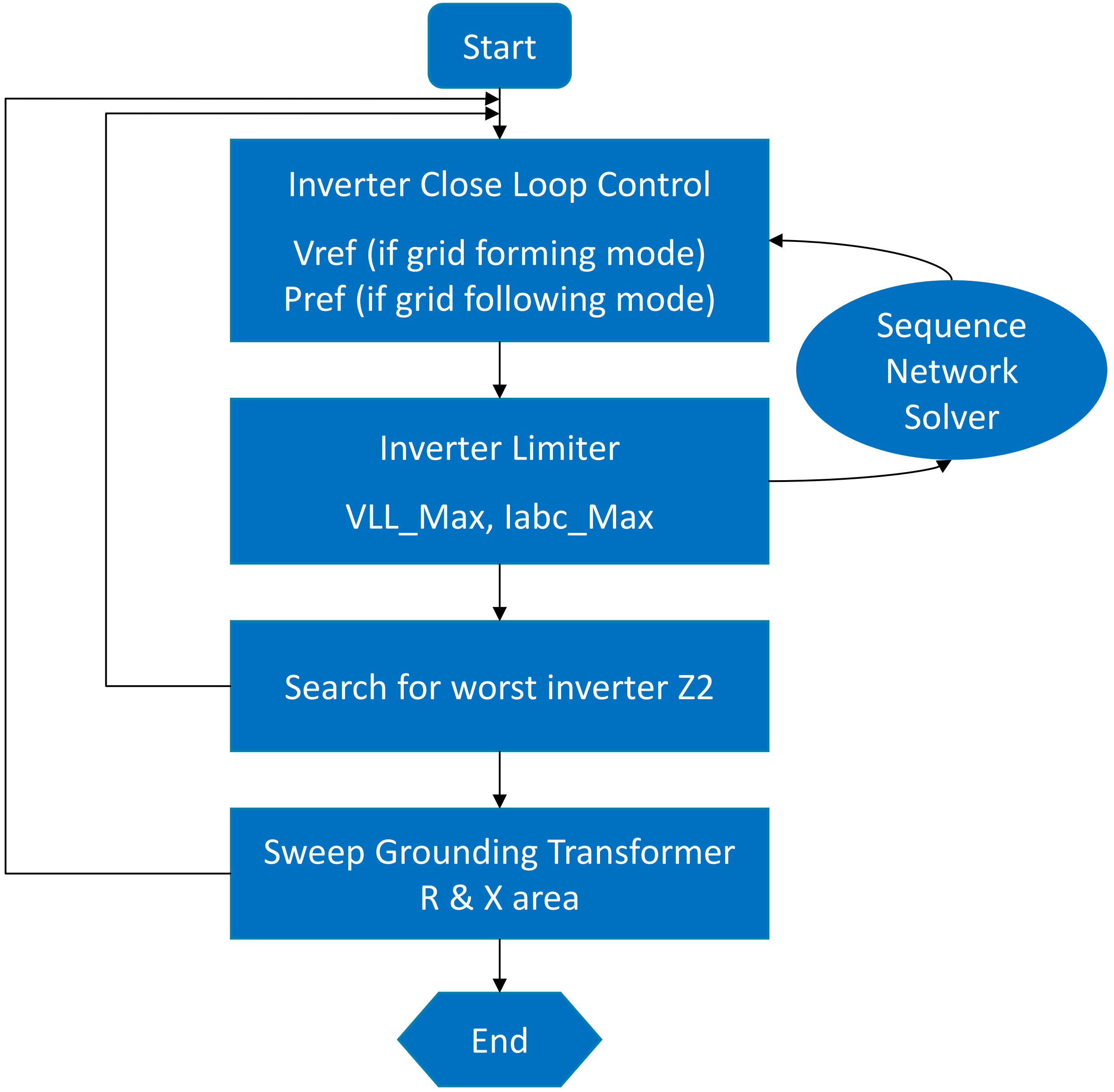
Note: Maximum feeder phase-ground voltage during fault is dependent on
a range of voltages (minimum to maximum) is provided in the results table



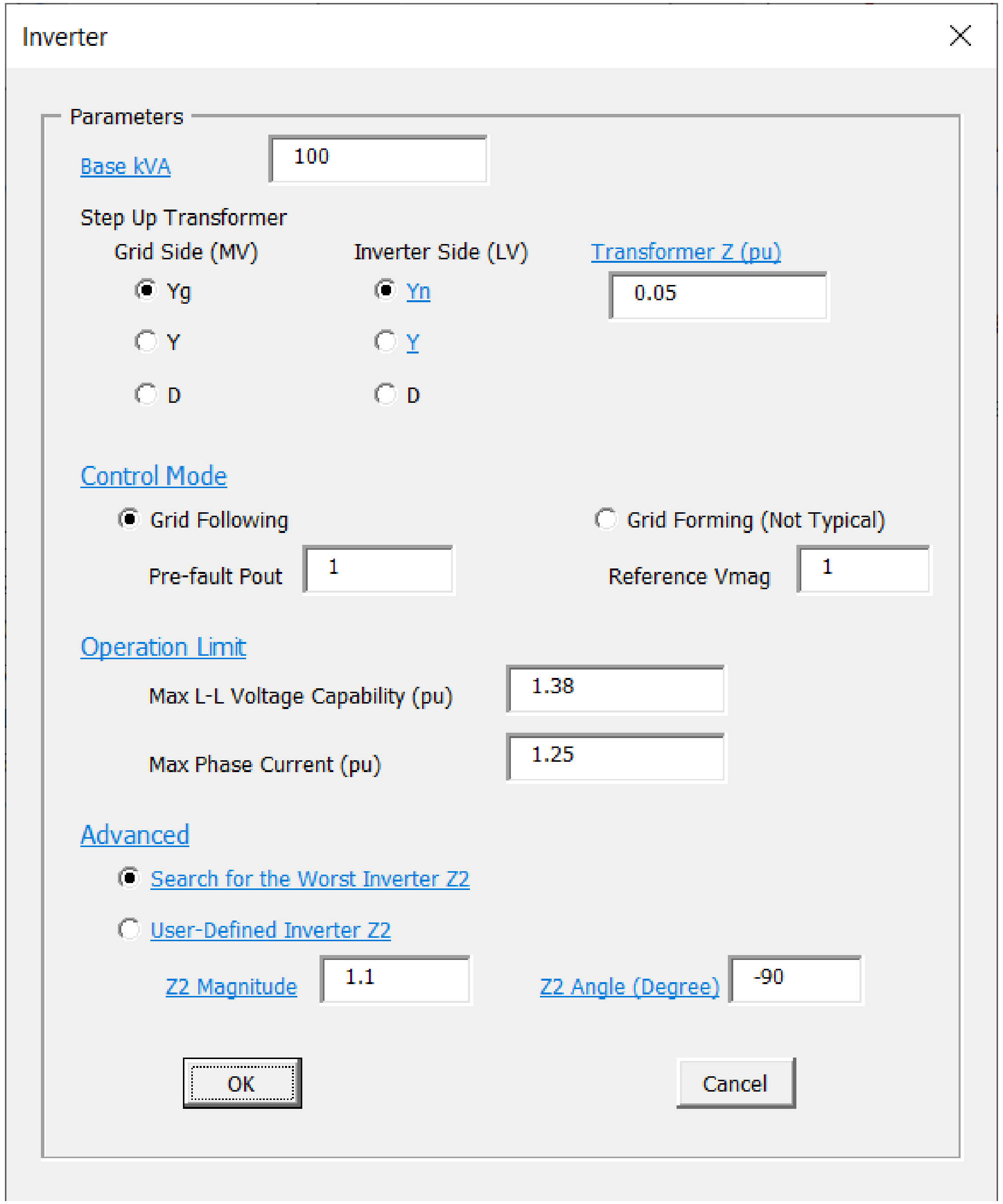


1. ***Excel VBA based tool to reduce dependency on commercial planning software***
2. ***Realistic inverter model with consideration of various GSU configurations***
3. ***Minimized data requirements for inverter model setup***
4. ***Automatically search for worst negative sequence behavior***
5. ***Color map to facilitate grounding impedance selection***

Calculation Algorithm



Inverter Parameter Form



Result of ISGT for the Previous Exemplar Circuit

Line to Ground Fault Simulation Result

Max. Feeder Phase-ground Voltage During Fault (pu	0.95 ~ 1.25
OV Flag (>1.38pu per IEEE1547 7.4.1)	
Inverter Pout (pu @ Inverter Base)	0.90
Generation to Min. Load Ratio	1.00
kW Loss in GT Neutral Resistor (assuming 4% V0)	0

Calculate Fault

About

Reset Data

Max_V vs. GT_R&X (for GT Zg Selection)

Help

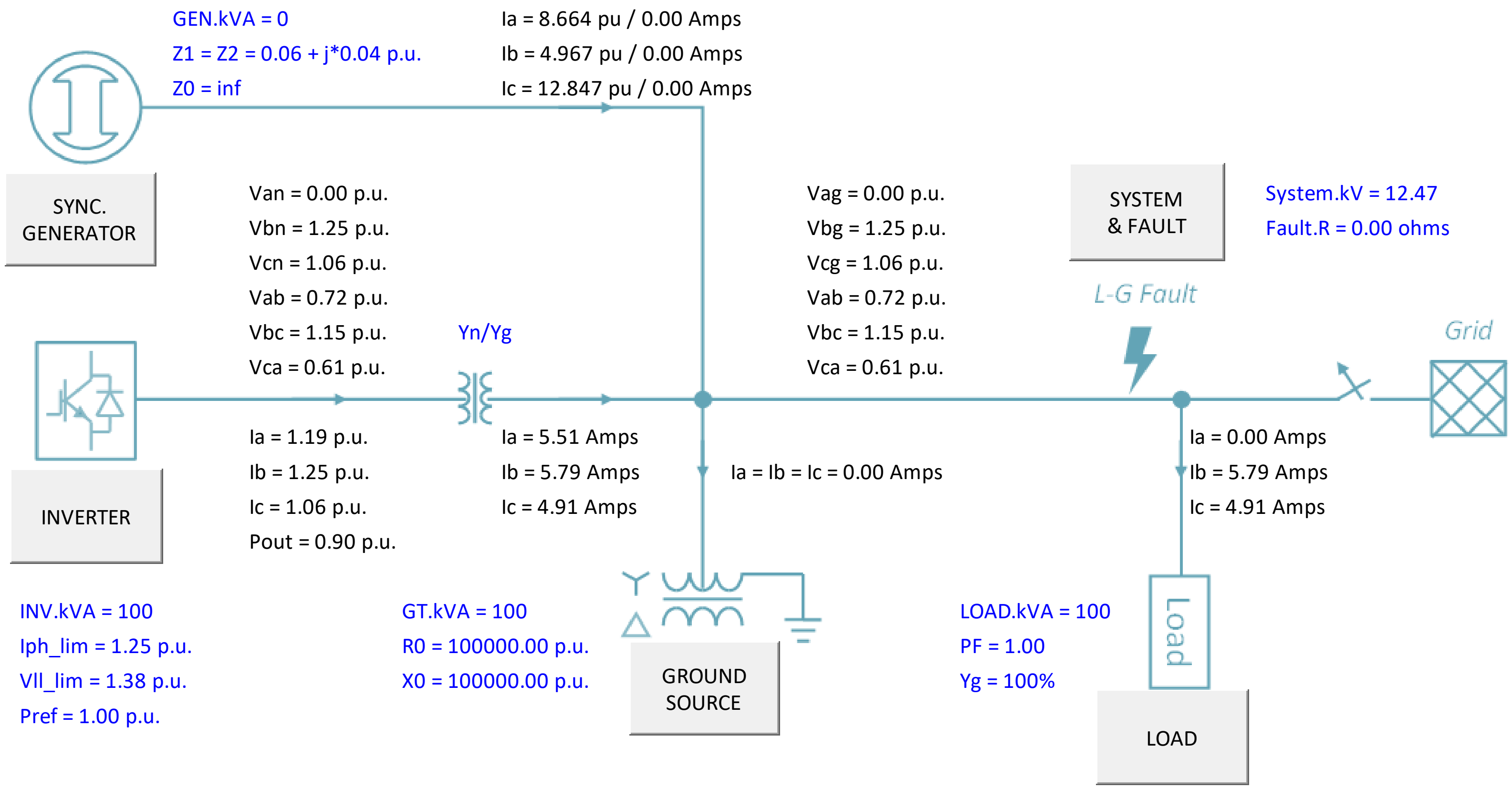
Note: Maximum feeder phase-ground voltage during fault is dependent on inverter negative sequence impedence (Z2), a range of voltages (minimum to maximum) is provided in the results table for user information.

Results are shown in black font and input data is shown in blue font.

TOV Risk:

Green = No risk of excessive TOV
Yellow = Some risk of excessive TOV
Red = High risk of excessive TOV

Risk is based upon the user entered grounding transformer inform

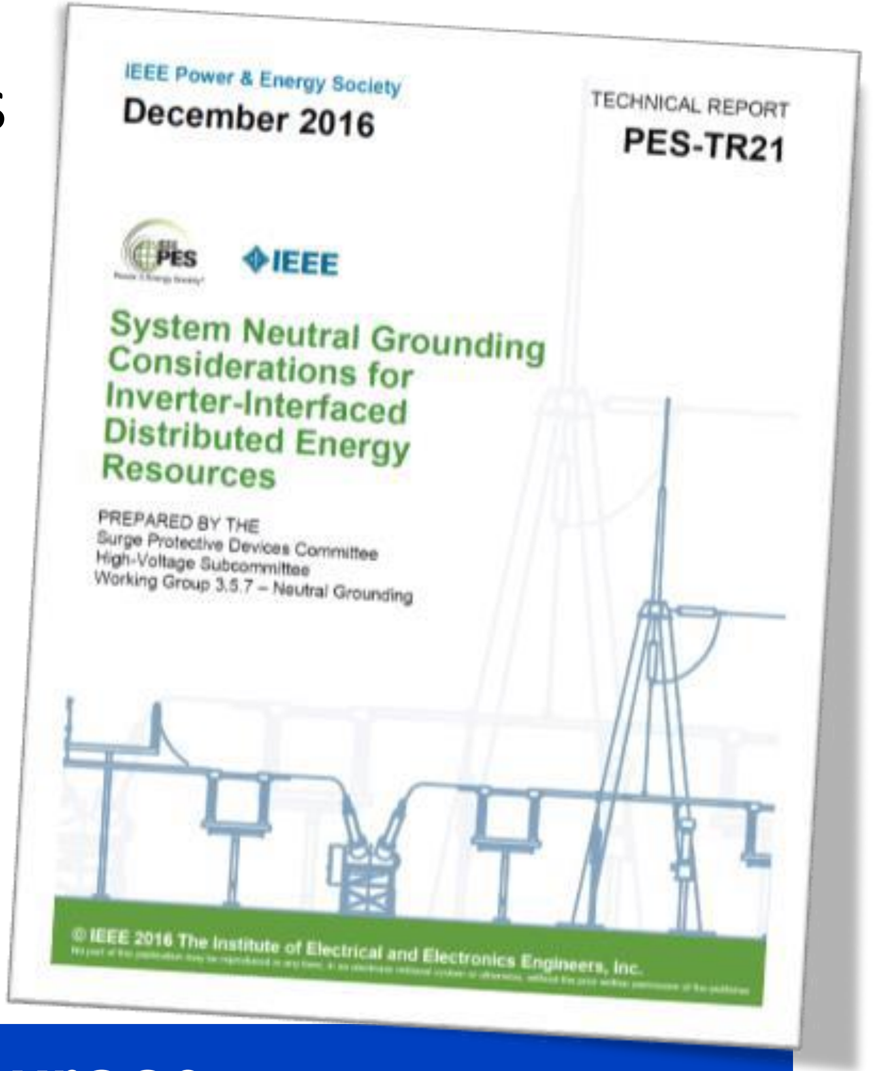


Mitigation Approaches

Neutral Grounding Guidelines, IEEE C62.92 Series:

- C62.92.1 – Introduction and definitions
- C62.92.2 – Synchronous generator systems
- C62.92.3 – Generator auxiliary systems
- C62.92.4 – Distribution systems
- C62.92.5 – Transmission and sub-transmission systems
- C62.92.6 – Systems supplied by current-regulated sources

Classical Effective grounding Practices for synchronous machines

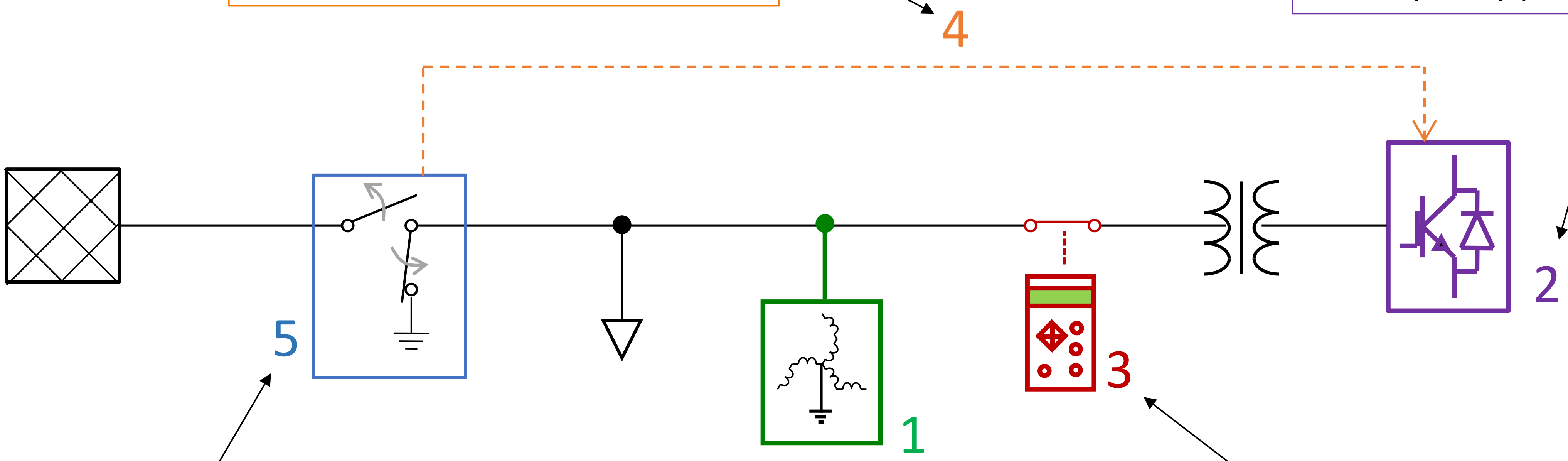


New guideline for inverter sources

Summary of Mitigation Approaches

Direct Transfer Trip (DTT)
- Send tripping signal to DER when circuit breaker opens

Inverter Control
- Anti-islanding
- Voltage protection
- Frequency protection



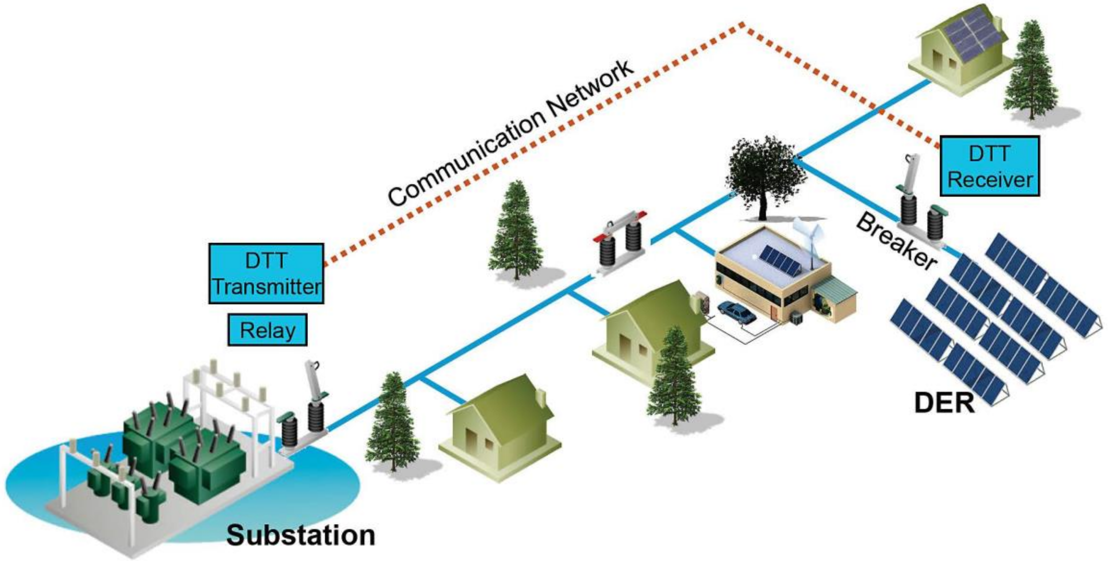
Grounding Switch
- Create short circuit to ground when breaker opens

Grounding Bank
- Mitigate neutral shifting that causes GFOV

Medium Voltage Recloser
- Utility-owned protective device to disconnect DER on MV over-voltage

Direct Transfer Trip (DTT)

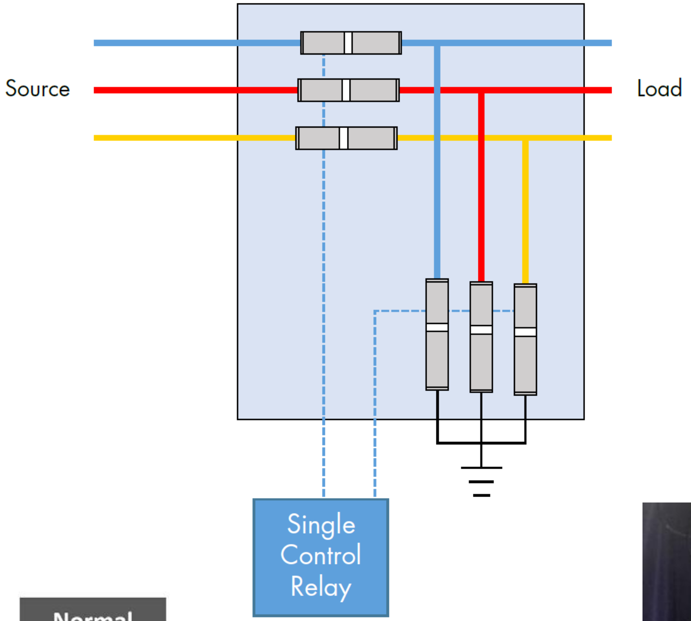
- ***Utility Direct-Transfer-Trip Survey Results***, 3002016638, Feb 2019
- ***An Update on Distribution Alternative to Prevent DER Islanding***, 3002015450, Dec 2019
- ***Detection and Protection for Unintentionally Islanded DER,*** 3002010999, Feb 2018
- ***Are Current Unintentional Islanding Prevention Practices Sufficient for Future Needs?,*** 3002003291, Dec 2015.



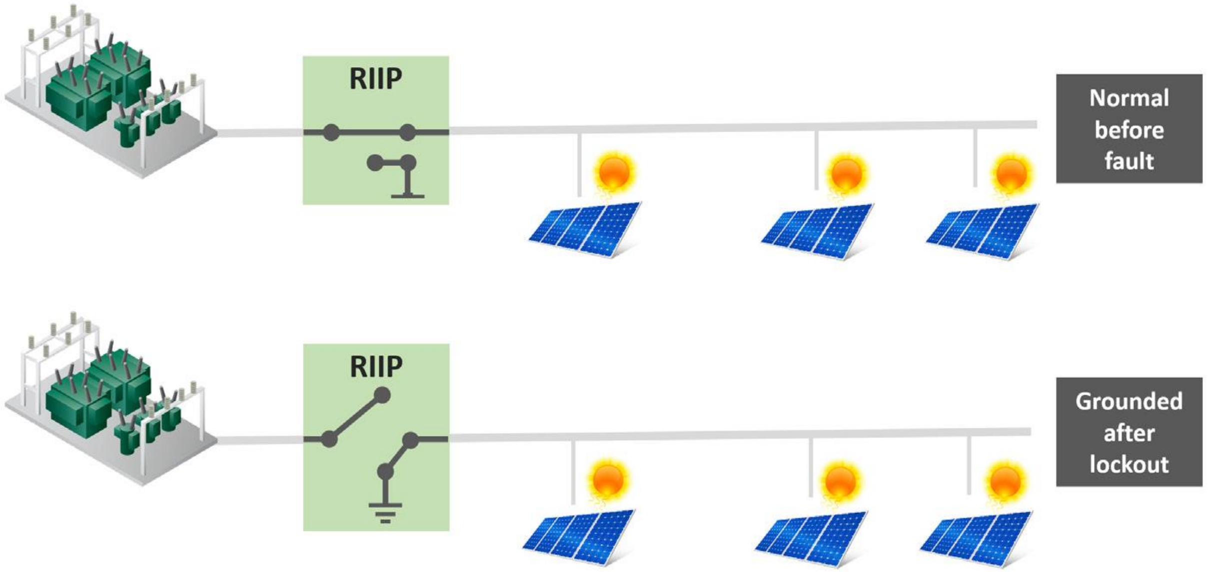
Technology	Reach	Benefits	Drawbacks
Copper wire	Short to Med	Very reliable, fast	High cost
Fiber	Med to Long range	Very reliable, fast	High cost
Cellular	Long range	Moderate cost / average reliability	Moderate reliability often needs two lines
Wireless (900 MHZ)	Short range	Low cost	Line of site required
Distribution SCADA	Long range	Easy integration, low cost	Too slow for protection applications
Analog telco lines	Alternate circuits	Available in many locations	May not be supported or becoming obsolete
Third party services	Med to long range	Reliable (normally use fiber)	May experience delivery delays
Power Line Carrier	Med to long range	Medium cost	Difficult to operate and maintain reliability

Grounding Switch

Auto-grounding system with series-connected fuse



Back-to-back reclosers, single control approach



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