Effective Grounding and Inverter-based DER

A “new” look at an “old” subject

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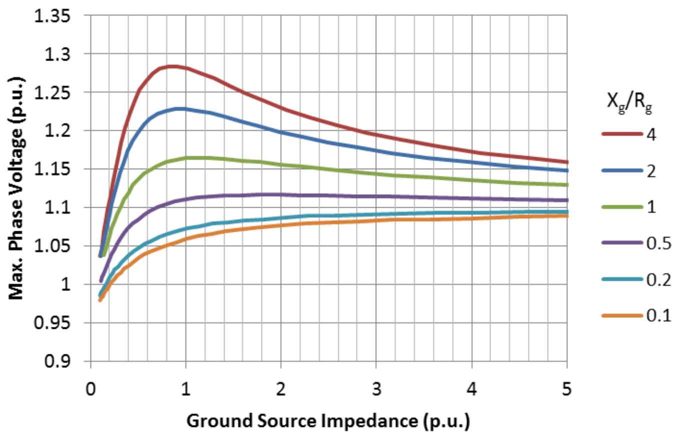
Welcome and Webcast Logistics

- Open dialog format
  - Phone lines “open” to help facilitate discussion…
  - …But please mute your phone when not speaking to reduce background noise
  - Use webcast console to alternatively submit questions

Webcast being recorded for re-listen and review. Yet, we encourage you to share personal views and engage in the discussion freely.

Project Objectives

- Address members “hot items” from Sept. Advisory
- Extend the work done under IEEE C62.92.6 (Reigh Walling and Ben York – Technical Report PES-TR21)
- Develop a guide to:
  - Understand the issue and differences in relation with synchronous generators
  - Have a proper quantitative knowledge of how parameters affect GFOV
  - Know where supplemental ground sources are needed
  - Select the proper ground source impedance
  - Assistance in developing screening criteria
- Webinar to inform members – Today!
- Tech Brief covering outcomes



Goals for Today

- Provide an overview of the work and outcomes
- Structured to get to conclusions quickly to initiate dialogue
- Get your questions, feedback, and guidance
- Adjust as necessary in written report

Background

- Traditional power system grounding (based on IEEE C62.92.1-5) addressed synchronous generators (***low-impedance voltage sources***)
- In 2017 IEEE C62.92.6 was added to address grounding of systems supplied by inverter DER (***current-regulated sources)***.
  - With few exceptions, grid-connected three-phase inverter DERs are controlled to act as positive-sequence current sources
  - This behavior is fundamentally different than machines, and calls for review and update of our effective (neutral) grounding practices for inverter connected plants.
- Currently PV plant grounding requirements are not harmonized among different utilities and between jurisdictions of the same utility

IEEE C62.92 Series: IEEE Guide for Application of Neutral Grounding in Electrical Utility Systems

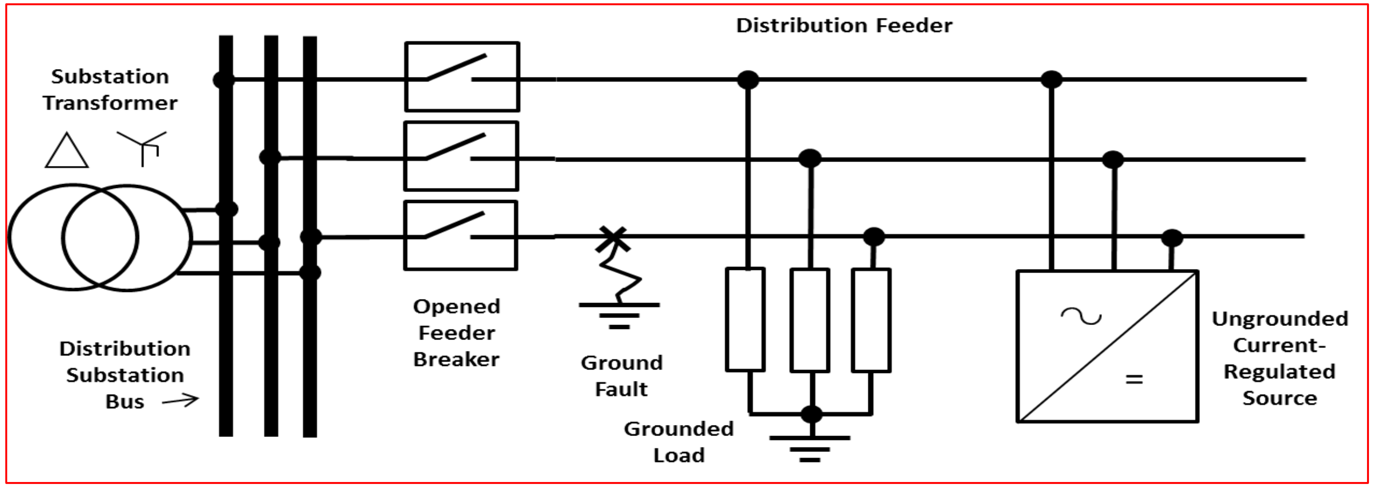
- C62.92.1 – Introduction and definitions
- C62.92.2 – Synchronous generator systems
- C62.92.3 – Generator auxiliary systems
- C62.92.4 – Distribution systems
- C62.92.5 – Transmission and sub-transmission systems
- C62.92.6 – Systems supplied by current-regulated sources

"…provides definitions and considerations related to system grounding where the dominant sources of system energization are current-regulated or power-regulated power conversion devices."

- Current EPRI analytical work addresses practical applications of C62
  - Screening of 3 or 4-wire DER connections w.r.t. primary transformer configuration
  - Supplemental grounding transformers, sizing, effectiveness, other options
  - Models used in short circuit protection tools (CAPE, ASPEN, CYME, Synergi)

System Grounding in the Unintentional Islanding Scenarios

1. Inverter DER are expected to have <u>insignificant</u> effect on system grounding when the feeder breaker is closed
   - Inverter fault current contribution ≈ rated current, System SCC >> Inverter Rating
2. There is <u>significant</u> concern about ground fault overvoltage (GFO) in case DER supports an unintentional island (feeder breaker open) with a ground fault
   - Normal system neutral ground source (substation) is removed
   - Duration of an island with a fault present is likely to be very short



GFO is the first order concern in this scenario

Example of DER Screening Practice: Used in FERC-SGIP, NY SIR, CA Rule 21 and most states

- Aim to screen out DER connections prone to ground-fault overvoltage (GFO) and to limit allowed connection types based on concerns for ground fault and open-phase
- This table is commonly used (but may not be appropriate for inverter DER)

Primary distribution line configuration	**Type of DER connection to primary**	**Result/Criteria**
Three-phase, three-wire	Any type	Pass
Three-phase, four-wire > 5 kV	Single-phase line-to-neutral	Pass
All Three-phase, four-wire (For any line that has sections or mixed three-wire and four-wire)	All others	Fail. To pass aggregate DER AC nameplate rating must be less than or equal to 10% of line-section peak load

- Failing the screen typically leads to alternatives such as adding a grounding transformer

Conventional Notion of an "Effectively Grounded Voltage Sources"

- Effective grounding is defined as a Coefficient of Grounding (CoG)

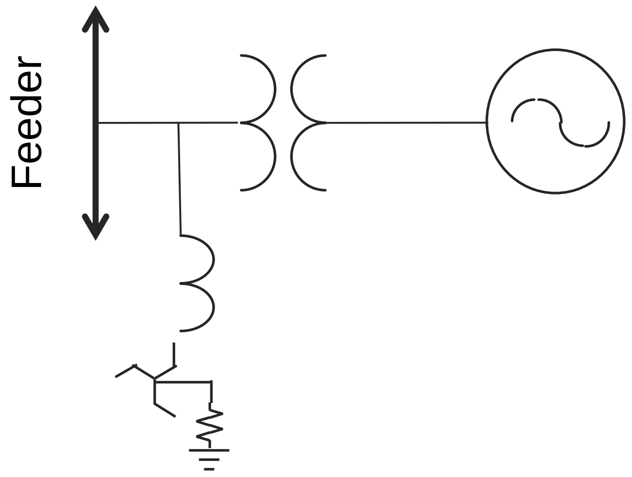
  ➡ ***CoG $\leq$0.8 pu limits GFO to 0.8 x $V_{l\text{-}l}$ or 0.8 x $\sqrt{3}$ ~ 138% of $V_{l\text{-}g}$***

  – ∴ effective grounding is a system condition defined by voltages
  – CoG $\equiv V_{L\text{-}G(fault)}/V_{L\text{-}L(no\ fault)}$
  – $X_0/X_1 \leq 3$, $R_0/X_1 \leq 1$ are an approximation (works for synchronous generators)

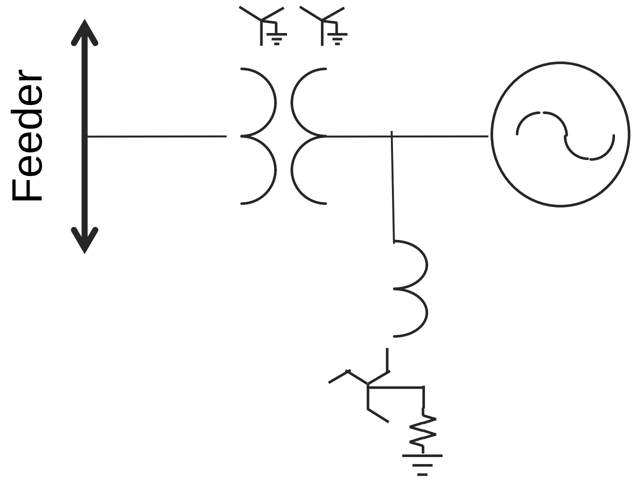
- Conventional situation:
  – Relatively low impedance of rotating generator sources dominates system
  – Loads and other shunt impedances are relatively unimportant to fault and GFOV calculations
  – Thus, a voltage source with a low X_0/X_1 will yield effective grounding when energizing any practical system

Typical Grounding Practices for Synchronous Generator DER

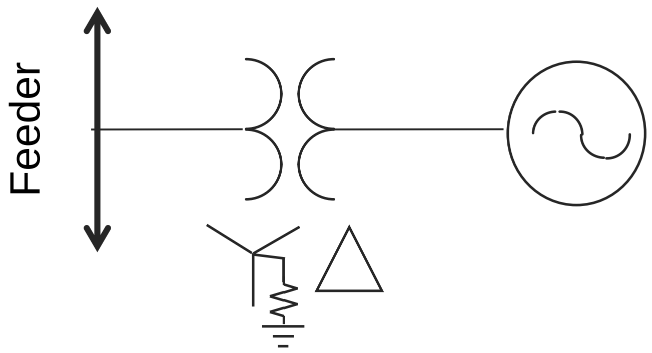
Grounding transformer on MV, GSU any configuration



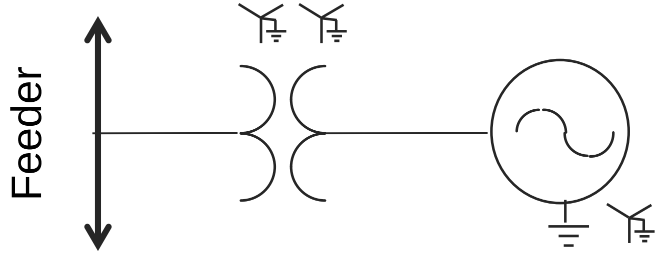
Grounding transformer on LV, GSU must be Yg-yg



Yg-Δ GSU, no separate GT needed, neutral resistor (options)

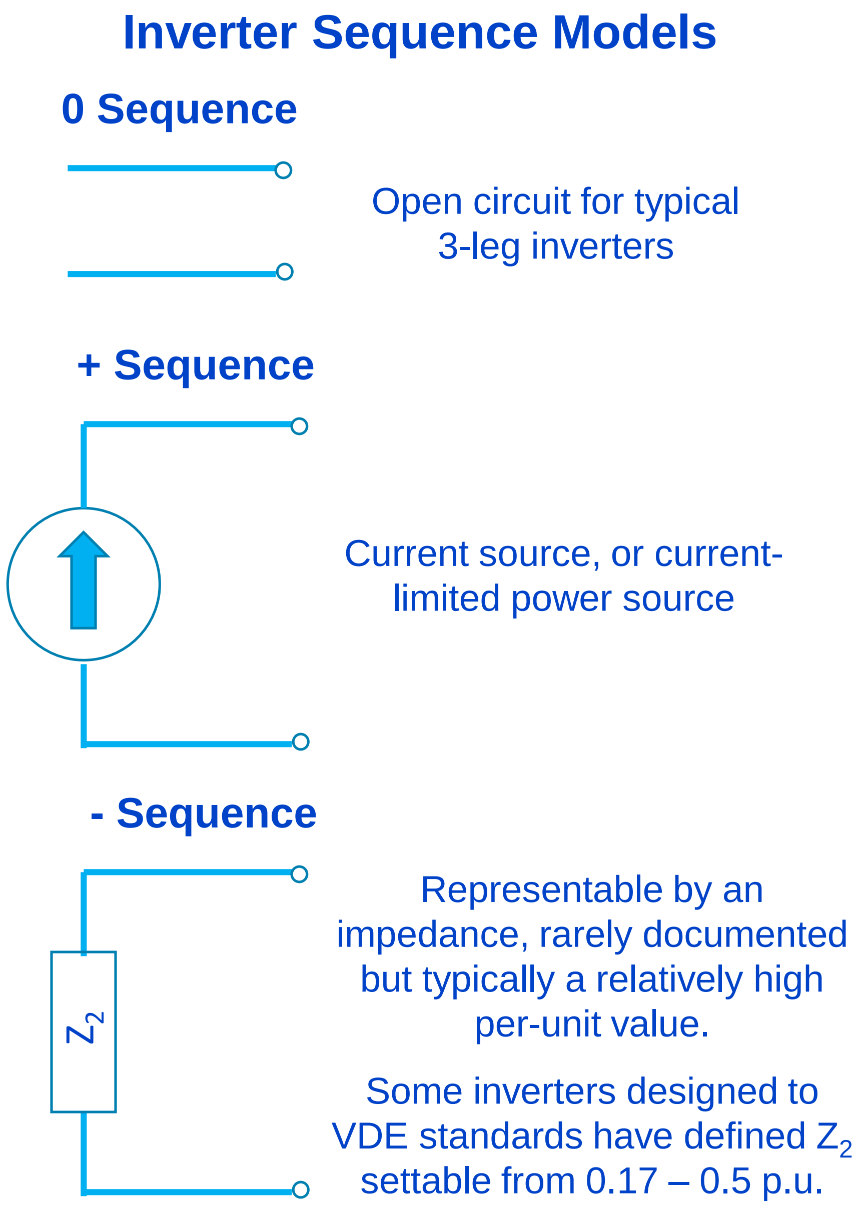


Grounded wye generator, GSU must be Yg-yg



Inverter Representation

- Current source or current-limited power source model is adequate for TOV evaluation
- Symmetrical component analysis is an appropriate analysis tool when three-phase inverters are involved
- Symmetric components do not fit where the dominant sources are the aggregation of single-phase inverters
  - Individual phase currents follow the terminal voltage phase
  - Does not create an equivalent positive-sequence source during unbalanced (e.g., ground fault) conditions



… Now with Current Sources

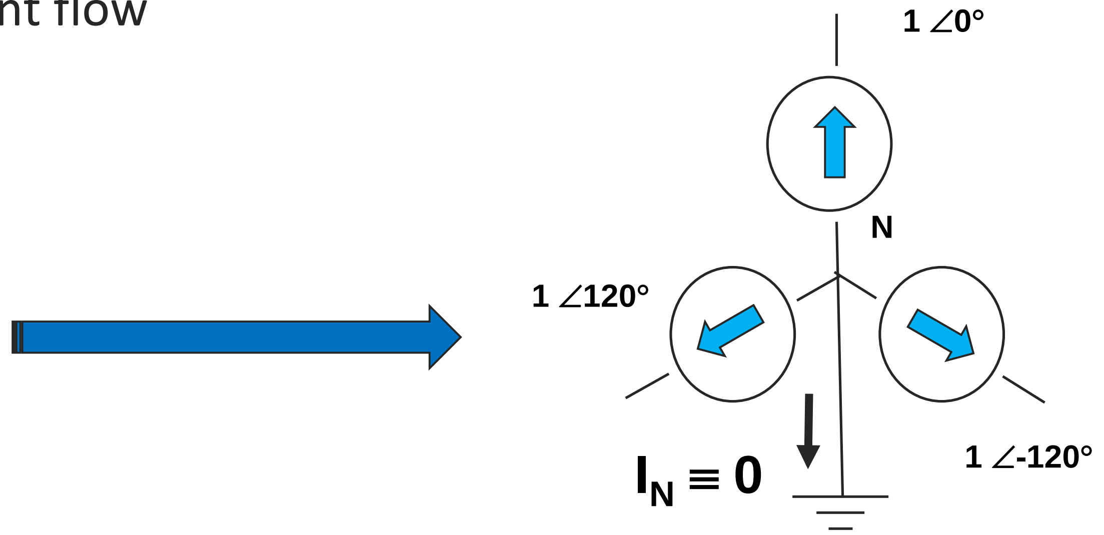
- Source impedance is inherently very high - ideal current source has infinite impedance
- Consider an ideal 3-phase 1 p.u. current source having 10,000 p.u. impedances connected phase to ground on output (e.g., a short section of cable charging)
  - $X_0/X_1 = 1$, $R_0/X_1 << 1$; so is this effectively grounded?
- Connect this source to 1 p.u. L-G-connected load impedance;
  $V_{L\text{-}L}$ with no fault = 1.73 p.u., $V_{L\text{-}G}$ with fault = 1.0 p.u.,
  this source + load; this <u>system is effectively grounded</u>
- Connect the same source to 1 p.u. Δ load,
  $V_{L\text{-}L}$ with no fault = 1.73 p.u., $V_{L\text{-}G}$ with fault = 1.73 p.u.,
  <u>system is not effectively grounded</u>
- ∴ For high-impedance sources, the system defines grounding
  - Concept of "effectively grounded source" loses relevance for high-impedance (i.e., inverter) sources

The Role of Loads in Inverter-Sourced Systems

- Shunt impedances (loads) are critical to systems driven by current sources
- Loads are typically ignored during short-circuit studies and calculations of GFOV where synchronous generators are the source
  - Source impedance << load impedance, ∴ loads don't matter much for synchronous generators
  - Situation is fundamentally different where the source is inverters; high source impedance
- But what if there are no loads present?
  - Theoretically, a current source driving into a circuit with no loads produces infinite voltage
  - Realistically, an inverter's control will push its voltage to a high limit in order to try to drive the current
  - Called a "load rejection overvoltage", inverter will typically trip very quickly
- Purpose of effective grounding is to avoid overvoltage
  - Grounding does not affect load-rejection overvoltage
  - System energized by a current source, but without load, will have severe overvoltage **with or without** ground source presence
- ∴ Grounding decisions based on no-load conditions do not serve a useful purpose

Does a Grounded Neutral Connection Make an Inverter a Grounded Source?

- Not necessarily, because:
  - Neutral may be just for measurement (IEEE Std 1547-2018 compliance) and without connection to the power circuit internally
  - Controls may impede any zero sequence current flow
    - In a wye-connected ideal positive sequence current source there is no neutral current, regardless of applied zero sequence voltage
    - This has a neutral connection but does this provide a ground source?
  - 3-phase inverter can be 3 x 1-phase inverters in one box

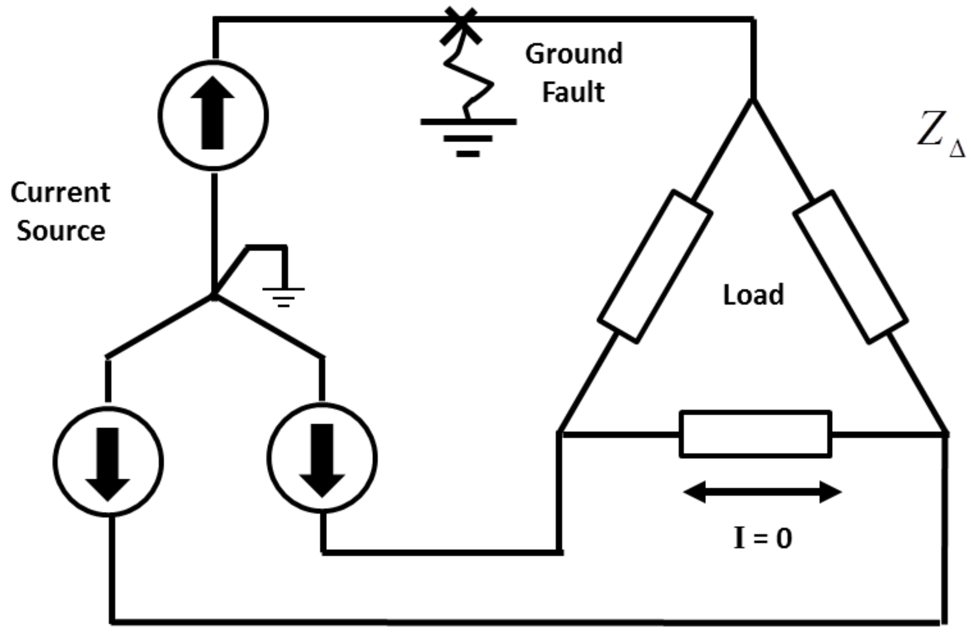


- Some inverters are designed to have low zero-sequence impedance
  - Typically for off-grid application
  - Relatively obscure

Aggregated Single-Phase Sources

Line-to-line connected loads

- If line-to-line loads are dominant, severe ground-fault overvoltage can occur even if single-phase inverters are connected line-to-neutral
- Current on the two unfaulted phases are equal in magnitude and in phase with each other because they each see the same voltage due to circuit symmetry
- Delta load impedance is three times the equivalent wye impedance
- Thus, the unfaulted phase voltage could theoretically reach 3 p.u.
- Inverter will saturate at its voltage limit
- **The grounded neutral connection of the single-phase inverters will not eliminate ground fault overvoltage!**



$$Z_{\Delta} = 3 \cdot Z_{Y}$$

Conclusions

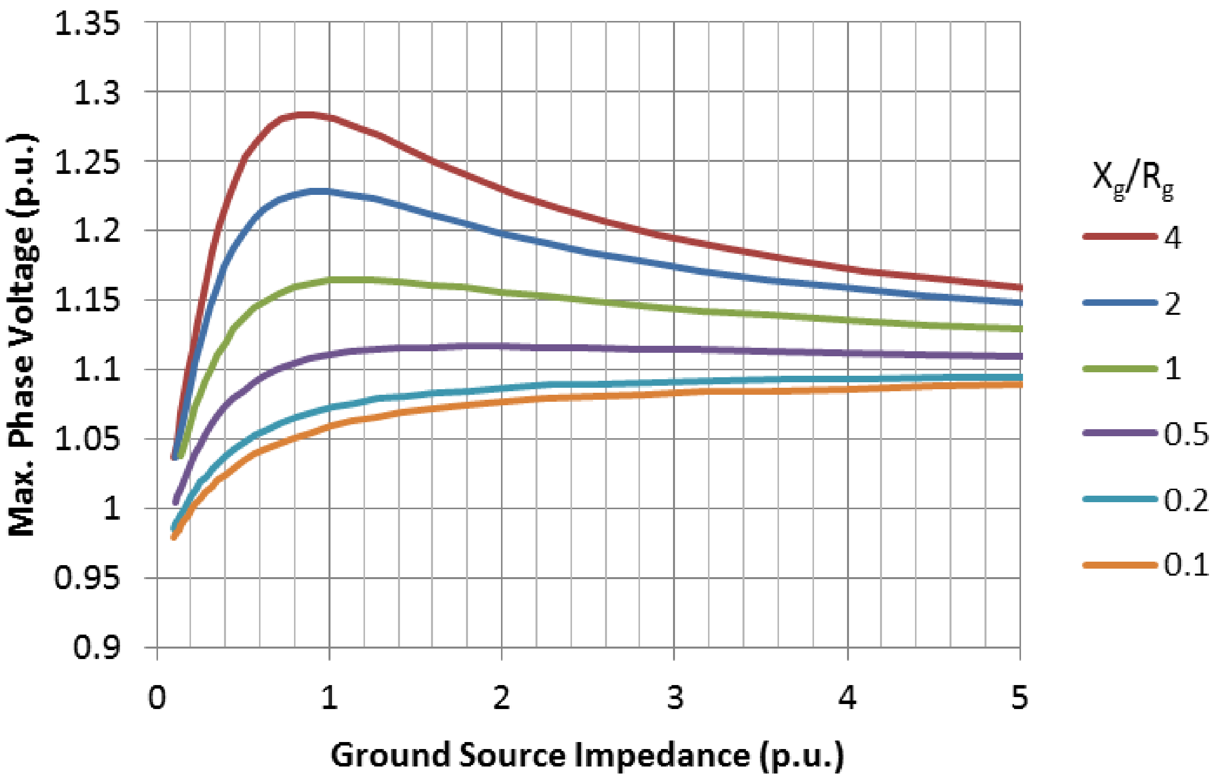
1. A ground connection on an inverter $\neq$ ground source
2. If more than 33% of loads are grounded, supplemental ground source is unnecessary
3. Adding a ground source can have adverse consequences
   - Reduced ground fault detection sensitivity
   - Increased arc flash risk
   - Maintains energization of open phases
   - Can increase ground fault overvoltage in some cases
4. If > 2/3 of loads are L-to-L connected, a ground source is necessary to ensure effective grounding when inverter sources an island
   - The ground source should have a Z_0 of around 2 – 3 p.u. resistive, rather than < 1 p.u. inductive as is commonly applied for synchronous generators
5. Widely used guidelines for supplemental grounds are not appropriate for inverter sources

Systems With Grounded-Wye Loads

Impact of Ground Source on Unfaulted-Phase Voltage

Grounded-Wye Loads

- Supplemental ground source not needed where loads are line-to-ground
- Typically-applied j0.6 p.u. ground source makes GFOV worse! (p.u. on DER base)
- Voltage levels will be proportionately higher if generation/load ratio greater
  - The 1.38 p.u. voltage level associated with effective grounding can be exceeded if generation is 108% of load, but would not be exceeded if no ground source is applied



Analysis Parameters:

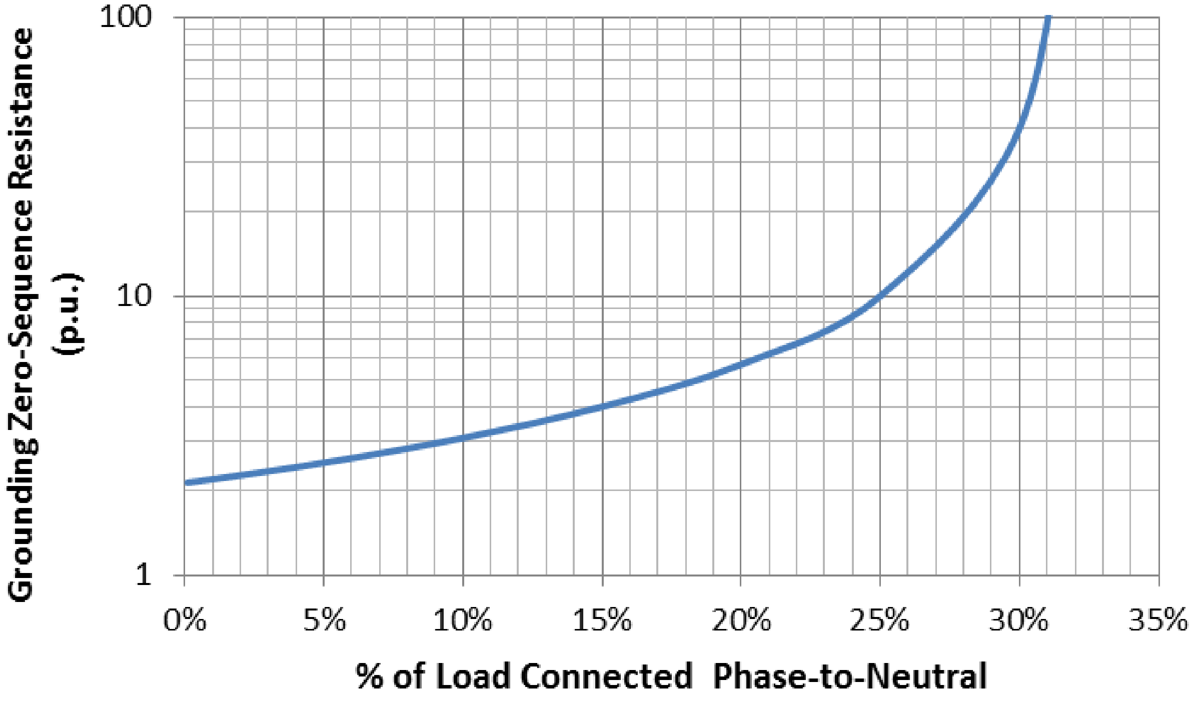
110% current limit, inverter negative sequence impedance = 100∠60° p.u., load pf = 0.95 capacitive

Ground Fault Overvoltages in Grounded-Wye Systems

- With L-N loads, ground faults in inverter-energized systems do not cause overvoltages due to “neutral displacement” unlike the case in voltage-sourced (e.g., synch. generator) situations
- Ground fault causes decrease in inverter active power output
  - $P_{fault} = 2/3\ P_{pre\text{-}fault}$ with constant inverter current output
- Most inverters have some form of constant active power regulation functionality
  - Positive-sequence current reference increased by power regulator in order to maintain initial active power
  - Increased current injection increases voltage (and power) on unfaulted-phases
  - For generation/load ratio = 1, the current injection and unfaulted phase voltages would rise to $\sqrt{3}/\sqrt{2} = 1.225$ p.u. if there are no limits to the injected current
- Response of power regulation depends on control design
  - If implemented as an outer control loop, it would tend to have a response time of many 60 Hz cycles
  - DER is quite likely to trip as a result of the fault prior to the power regulator reaching its goal
  - Power regulation could also be implemented as a feed-forward control and potentially faster
- Typically, there is a limit on the current regulator setpoint
  - Current reference limit is dependent on inverter design and control settings
  - A limit of 1.1 p.u. is typical as it allows rated power operation at ≈ 0.9 p.u. voltage for unfaulted condition

Need for Supplemental Ground Sources

- Although supplemental ground sources are unnecessary for 100% L-N load, resistive ground source is preferred if one is applied
- Figure below shows grounding resistance required for effective grounding as a function of percentage of L-N load
- No ground source needed if L-N loads are > 33% of total
- This is almost always the case on multi-grounded wye (4-wire) feeders
- Three-wire feeders have only L-L loads, but are designed to tolerate GFOV, and added ground sources are highly disruptive to their protection schemes



Impact of Ground Sources on GFOV in Grounded-Wye Systems

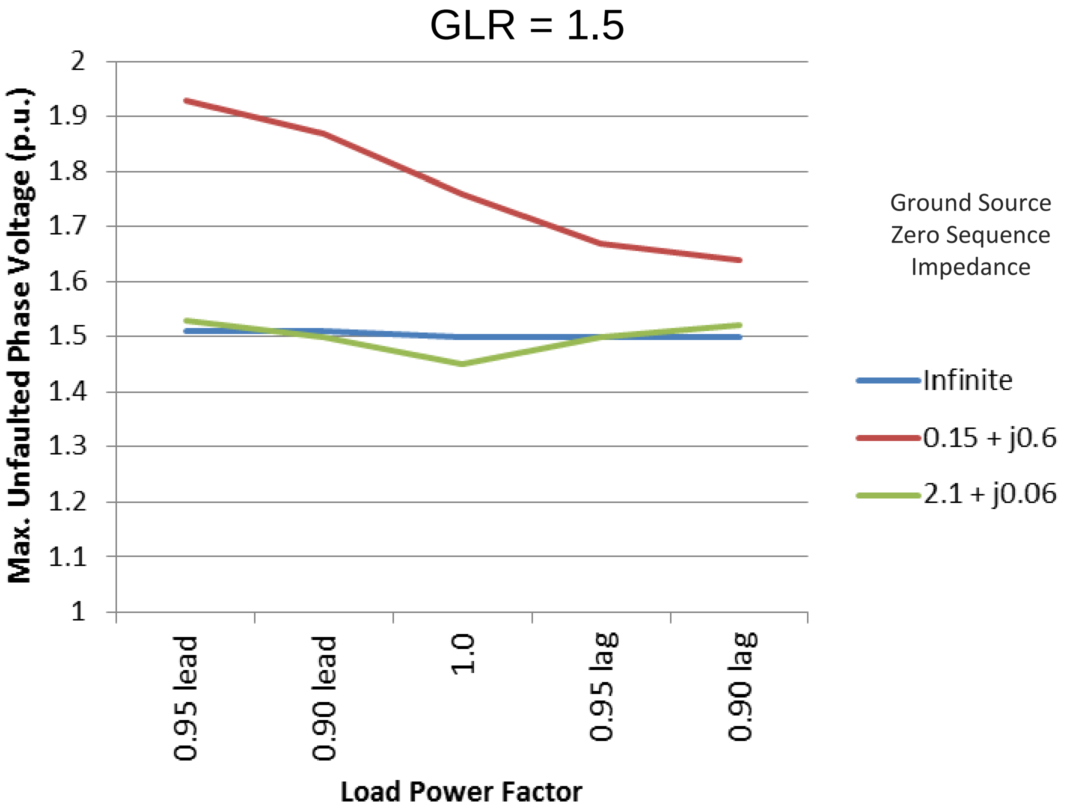
- Because overvoltage is a power regulation issue, ground sources have non-apparent impacts
- Inductive ground sources
  - Inductive ground sources cause power to decrease, causing power regulator to increase current
  - Differences in impedance of the zero sequence network (load and ground source in parallel) relative to the impedance of the negative sequence network (load only, assuming the Z_2 of the inverter is very large) increases voltage on one unfaulted phase
  - Example: j1 p.u. Z_0 causes current to rise to 1.27 p.u. (if unlimited) and max. unfaulted phase voltage to rise to 1.46 p.u.
- Resistive ground sources
  - Resistive ground source also cause power to decrease, causing power regulator to increase current
  - Do not interact adversely with load negative-sequence impedance
  - Example: 1 p.u. R_0 causes current to rise to 1.32 p.u. (if unlimited) but max unfaulted phase voltage rises only to 1.18 p.u.

High Generation/Load Ratios (GLR)

- $P_{DER} > P_{load}$ will create an overvoltage for islanding without a sustained ground fault
  - Termed “Load Rejection Overvoltage” (LROV) in the industry
  - With constant current injection by DER: $\overline{V}_{LROV} \approx \frac{\overline{P}_{DER}}{\overline{P}_{Load}}$
  - With power regulation: $\overline{V}_{LROV} \approx \sqrt{\frac{\overline{P}_{DER}}{\overline{P}_{Load}}}$
  - Initial higher LROV may decrease when power regulator responds
- Ground sources provide no mitigation of LROV when no ground fault is present
- Islands without sustained ground faults are a realistic possibility
  - Ground fault arcs that cause a feeder trip may extinguish when feeder breaker opens due to low fault current from DER, thus leaving DER islanded without a fault
- Inverters have limits to their output voltage
  - Maximum voltage depends on inverter design, dc source characteristics
  - Voltage limit can be implemented in various ways, depending on inverter design

Impact of Ground Sources with High GLR + Ground Fault

- Based on analysis assuming inverter does not reach a voltage limit:
  - At high generation/load ratio, inductive ground sources may increase overvoltage
  - Resistive ground sources provide only very marginal decrease in GFOV compared to no ground source
- Ground source does not address the fundamental LROV problem
- No significant benefit, potential adverse impact applied where loads are connected line to neutral



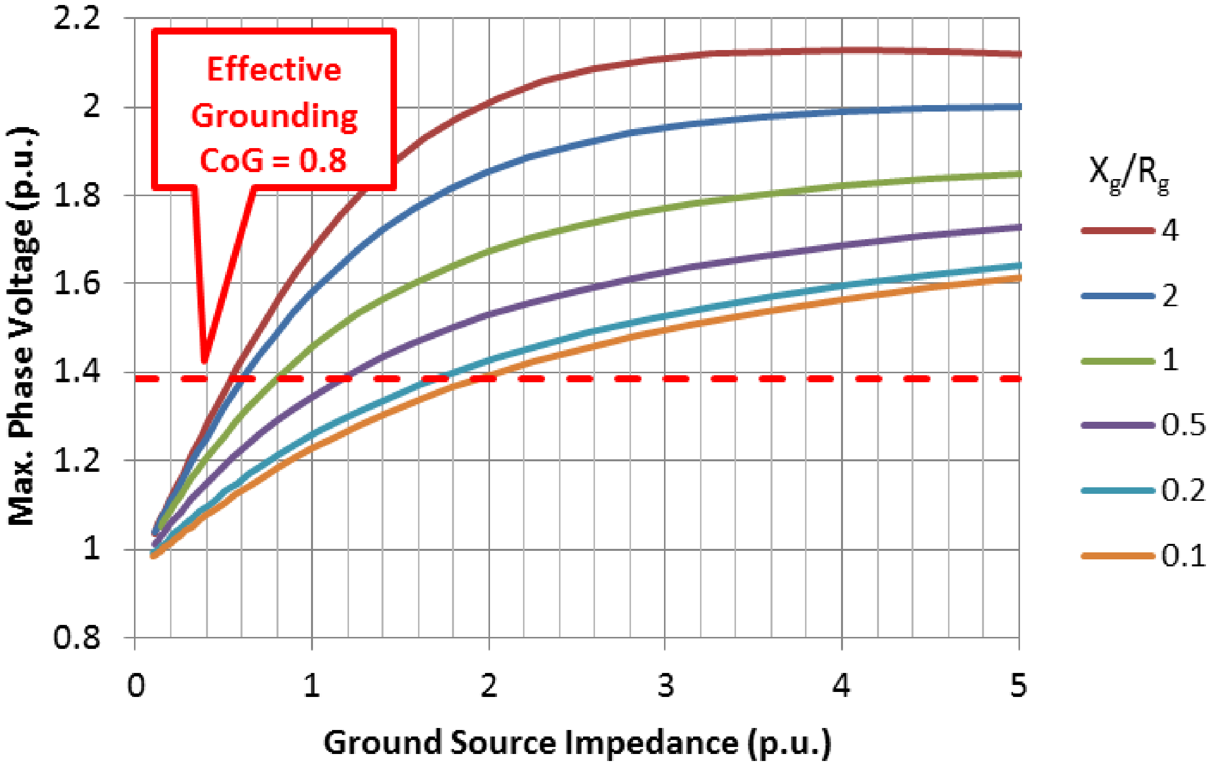
Loads are all L-N connected

Systems With Predominately Line-to-Line Loads

Impact of Ground Source on Unfaulted-Phase Voltage

Line-to-Line Loads

- Loads do not provide system grounding
- Supplemental ground source needed to provide effective grounding
- Resistive ground source provides much better GFOV limitation than reactive ground source

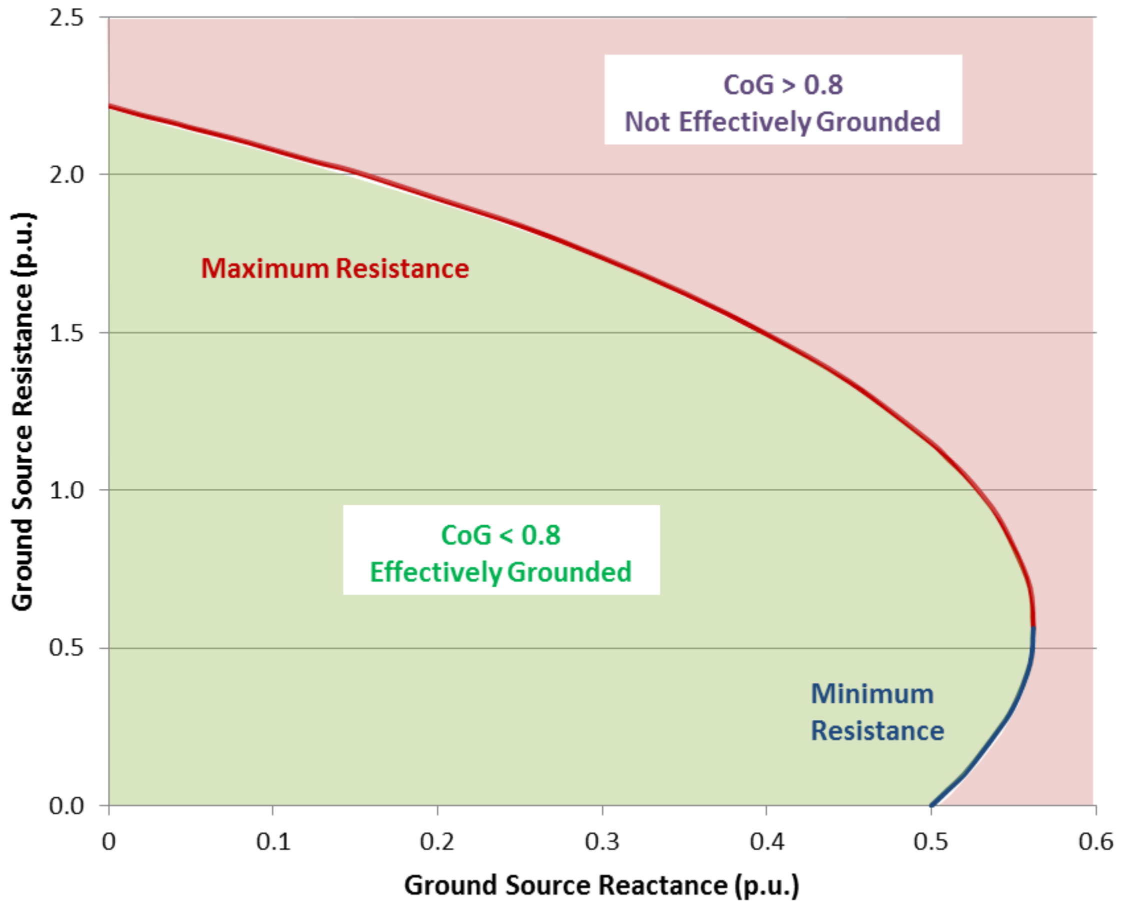


Analysis Parameters:

110% current limit, inverter negative sequence impedance = 100∠60° p.u., load pf = 0.95 capacitive

What Ground Source Impedance Is Required for Effective Grounding?

- For 100% delta loads, ground impedance needs to be within constraints of R and X shown below in order to have a CoG of 80% (effective grounding):
  - At higher reactance values, there is a minimum resistance as well as a maximum
  - For the conservative parameters assumed, effective grounding is not provided for a ground source zero sequence impedance > 0.562 + j0.562 p.u.



Assumed Parameters:

110% current limit, inverter negative sequence impedance = 100∠60° p.u., load pf = 0.95 capacitive

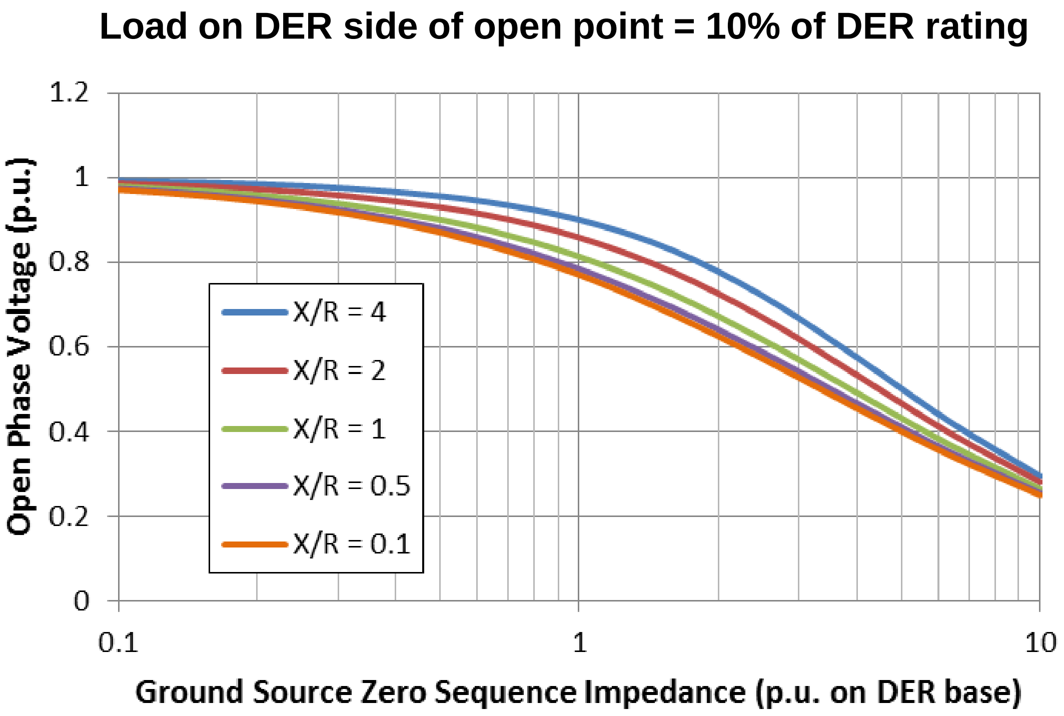
Adverse Impacts of Supplemental Ground Sources

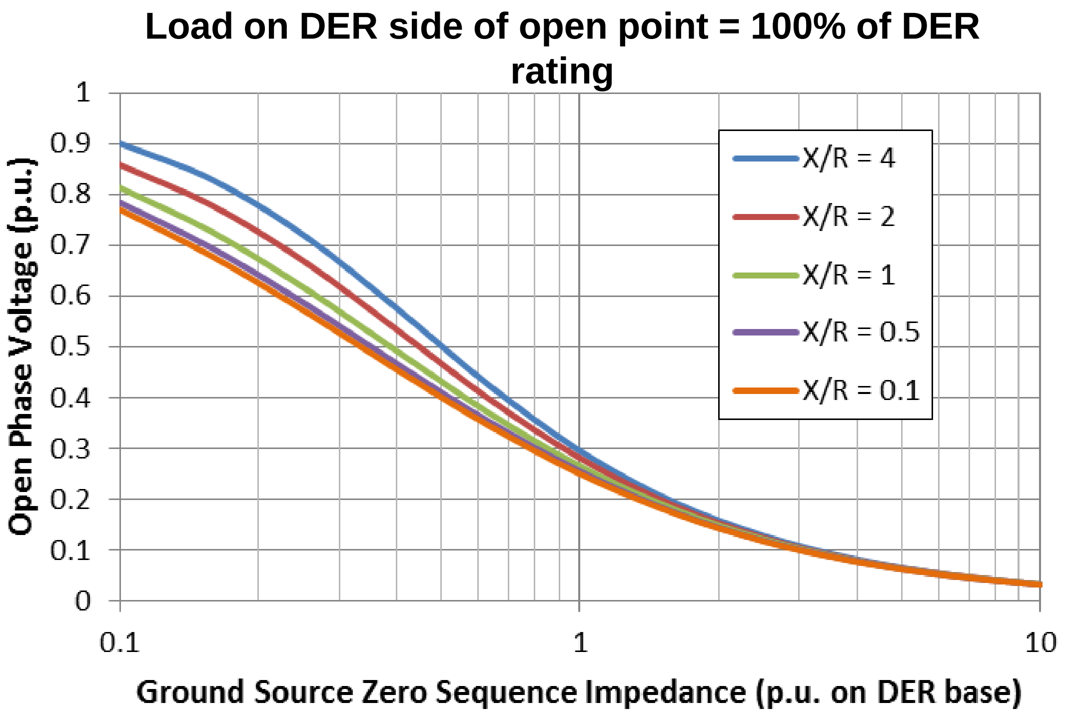
Pitfalls of Inappropriate Supplemental Ground Source Impedance

- Increase, rather than decrease, in GFOV
- Interference with ground overcurrent protection
  - Reduced relay I_0 with smaller $|Z_{GT}|$
  - Longer clearing times
- Increased ground fault current magnitude with feeder breaker closed
- Increased arc flash hazard, primarily from slower clearing
- Maintaining energization of an open phase
  - Lower $|Z_{GT}| \rightarrow$ stronger source
  - Inductive Z_{GT} more likely to result in overvoltage condition
- Cost of the ground source
  - Lower $|Z_{GT}| \rightarrow$ higher kVA/kW $\rightarrow$ higher $$
  - Inductive reactance kVA typically more costly than resistive kW (short-term rating)

Impact of Ground Sources on Open Phase Situations

- A ground source connected to a feeder has the adverse impact of “reconstructing” a phase voltage when there is an open phase upstream
- Plots below show open-phase voltages after DER has tripped

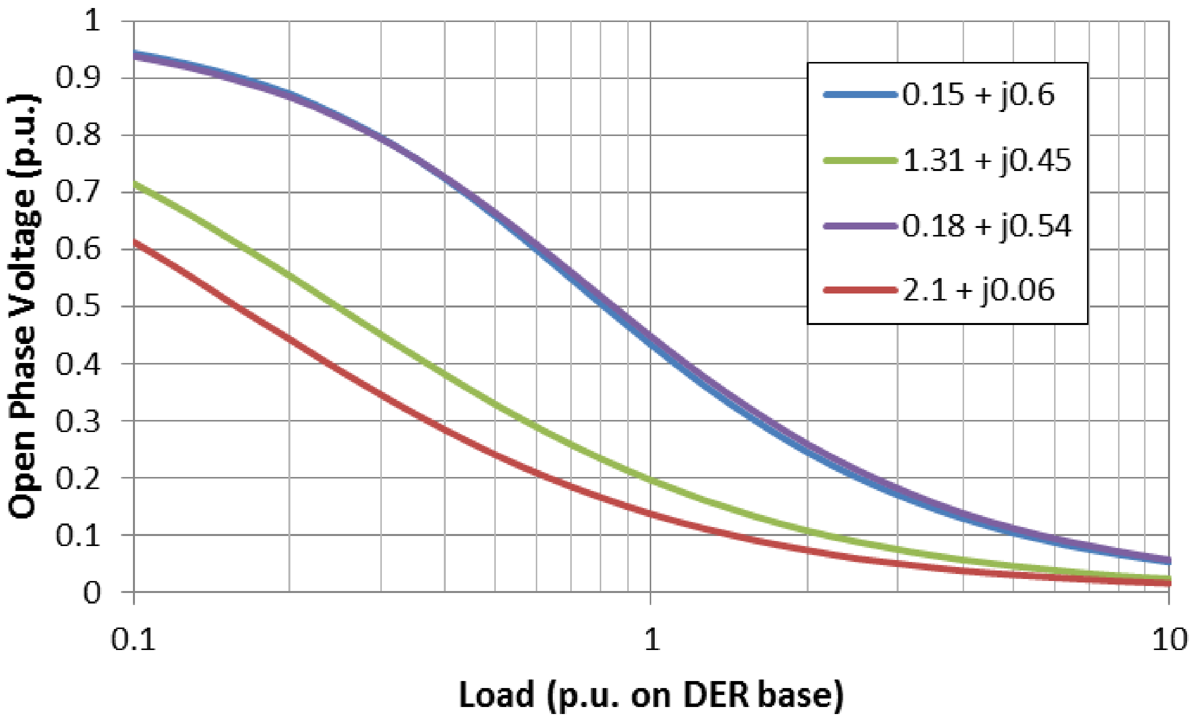




Open Phase Conditions

Impact of load and ground source impedance

- Plot below shows the open-phase voltage as a function of the line-to-neutral load connected downstream of open point for various ground source impedances

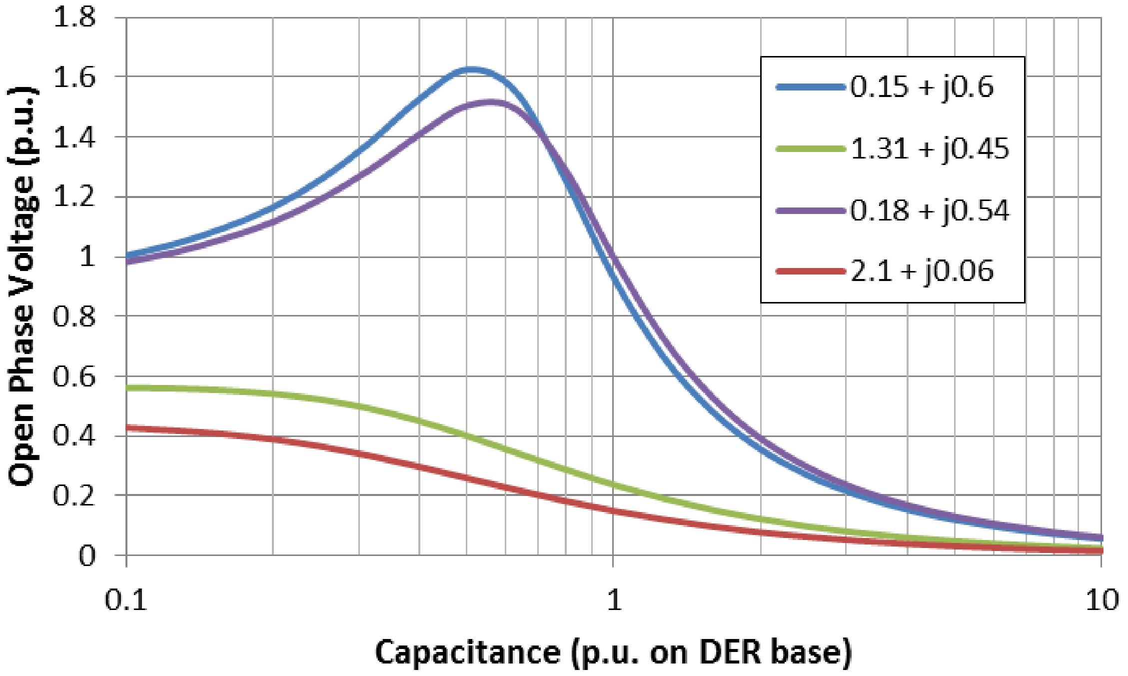


- Ground sources can cause substantial voltage to be present on opened phases

Open Phase Conditions

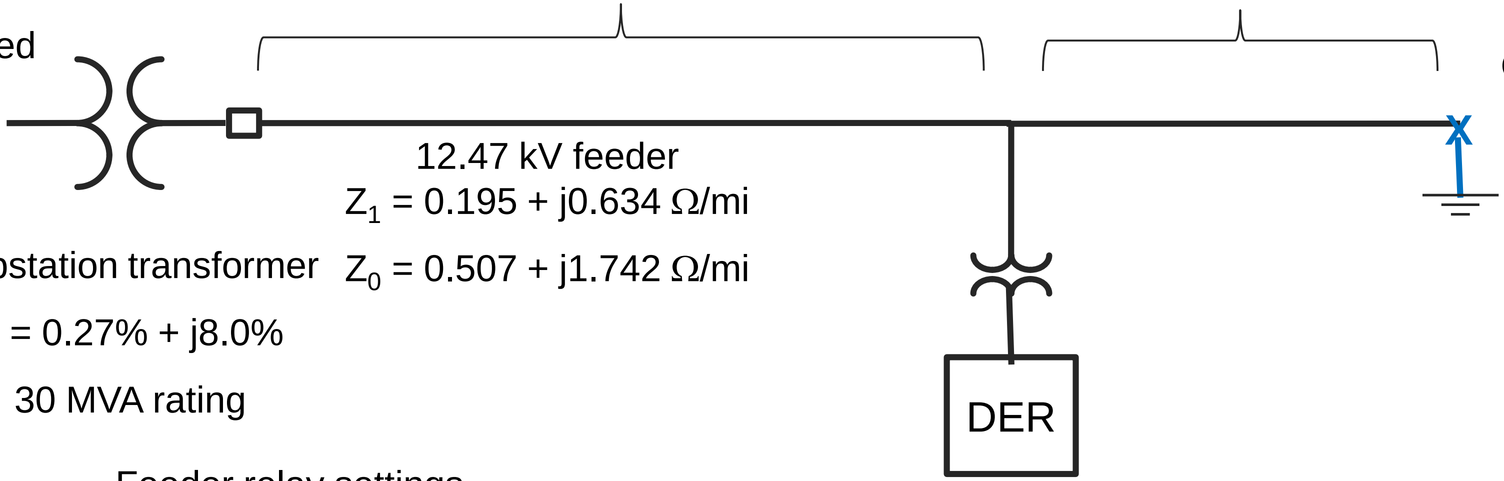
Resonance with capacitor banks

- An open phase condition can potentially leave a feeder capacitor bank downstream of the open point.
- If load is light on the section downstream of the open point, an inductive ground source can establish a 60 Hz resonant condition with the capacitor, potentially producing severe overvoltage.
- Example case with load on the downstream section equal to 20% of DER rating for various ground source impedances



Case Study to Compare Supplemental Ground Options and Evaluate Impacts

Example System for Comparing Grounding Options



Substation transformer

Z = 0.27% + j8.0%

30 MVA rating

Feeder relay settings

Instantaneous ground O/C - pickup = 1851 A

Instantaneous relay operating time = 1 ~

Time ground O/C – pickup = 347 A, TD = 1

Extremely inverse characteristic

Breaker operating time = 3 ~

Inverter-coupled DER

5 MW rating

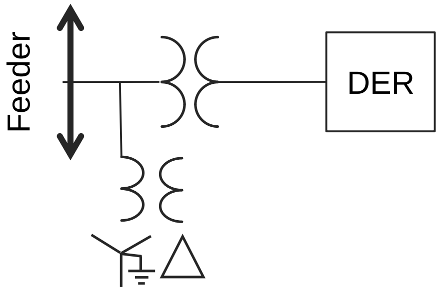
Fault current = 1.1 p.u.

DER is pure positive sequence current source (Z_2 assumed to be ∞)

Supplemental Grounding Options in Case Study

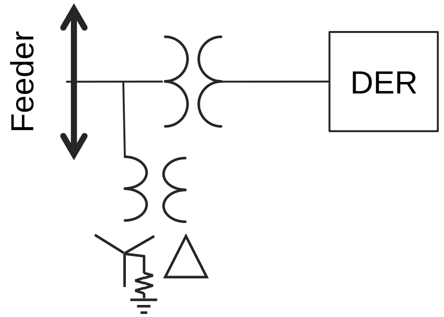
Conventional Option

- Grounding transformer providing Z_0 = 0.6 p.u.
- No added neutral impedance
- Can also be zig-zag
- Could also be on secondary if GSU is Yg-yg, but step-up's impedance must be considered and requires a larger GT kVA rating



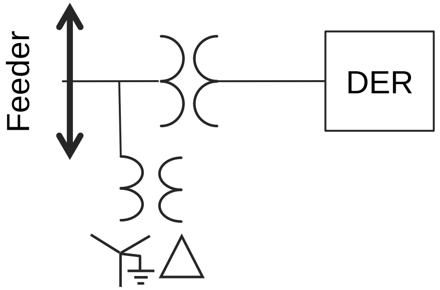
Optimized Option #1

- GT with neutral resistor proving net Z_0 = 1.31 + j0.45 p.u.
- Can also be zig-zag
- Could also be on secondary if GSU is Yg-yg, but step-up's impedance must be considered and requires a larger GT kVA rating



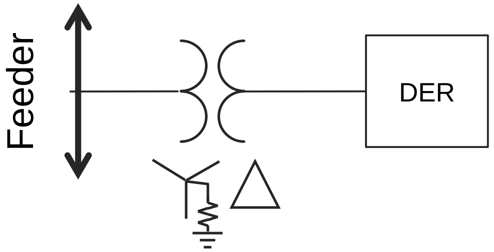
Optimized Option #2

- "Naked GT" providing Z_0 = 0.18 + j0.54
- No added neutral impedance
- Can also be zig-zag
- Could also be on secondary if GSU is Yg-yg, but step-up's impedance must be considered and requires a larger GT kVA rating



Optimized Option #3

- GSU transformer with neutral resistance
- Provides Z_0 = 2.1 + j0.06
- Full rating of transformer provides a smaller reactance (on DER base) than separate GT, allowing a larger resistance
- Can also be zig-zag / wye (obscure)



Comparison of Grounding Options for Example Case

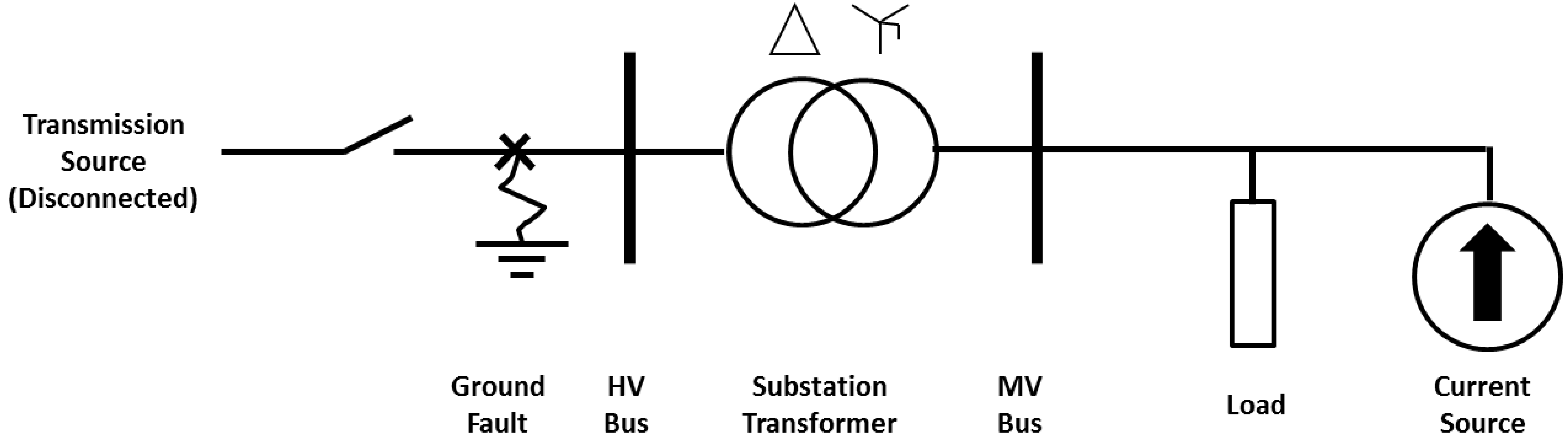
	No Ground Source	"Conventional" GT Option	Option #1 GT with $R_{neutral}$	Option #2 GT only	Option #3 $R_{neutral}$ on GSU
Z_0 (p.u. of MW rating)	∞	0.15+j0.6	1.31 + j0.45	0.18 + j0.54	2.1 + j0.06
Maximum phase voltage	1.10 p.u. (L-N loads) 1.90 p.u. (L-L loads)*	1.27 p.u. (L-N loads) 1.44 p.u. (L-L loads)*	1.10 p.u. (L-N loads) 1.38 p.u. (L-L loads)	1.24 p.u. (L-N loads) 1.38 p.u. (L-L loads)	1.07 p.u. (L-N loads) 1.38 p.u. (L-L loads)
Additional grounding equipment required	None	1 transformer (Yg-Δ or ZZ) + 1 neutral reactor	1 transformer (Yg-Δ or ZZ) + 1 neutral resistor	1 transformer (Yg-Δ or ZZ)	5 neutral resistors
Grounding transformer rating	None	500 kVA, 3.16% IZ, X/R=3	225 kVA, 2.18%IZ X/R=2.5	500 kVA, 5.83%IZ X/R = 2.5	None
Neutral resistor/reactor	None	j3 Ω, X/R = 5.7 44.9 A continuous 531 A 10-second fault	11.7 Ω, 20 A, 4.7 kW continuous 8.3 MJ 10-second fault	None	109 Ω (each) 2.6 A, 760 W cont. (each) 1.4 MJ 10-sec fault (ea)
Available ground fault current at PCC	1621 A	1925A	1724 A	1949 A	1662 A
End of feeder ground fault clearing time	3.21 seconds	5.19 seconds	3.67 seconds	5.39 seconds	3.37 seconds
Arc flash energy for end-of-feeder fault (% of no ground source case)	100%	184%	120%	193%	107%

* Coefficient of grounding > 0.8, this option does not provide effective grounding

Transmission Backfeed

Transmission Backfeed

- Line-to-neutral loads must be at the system level where the ground fault occurs in order to provide grounding
- Situations where DER backfeeds transmission is a common example where this is not the case (for transmission ground faults that can leave transmission assets islanded)
  - Transmission line-to-ground voltage is ≈ 1.73 p.u. regardless if distribution load is L-N or L-L connected, or if there is a ground source at the distribution level



Summary

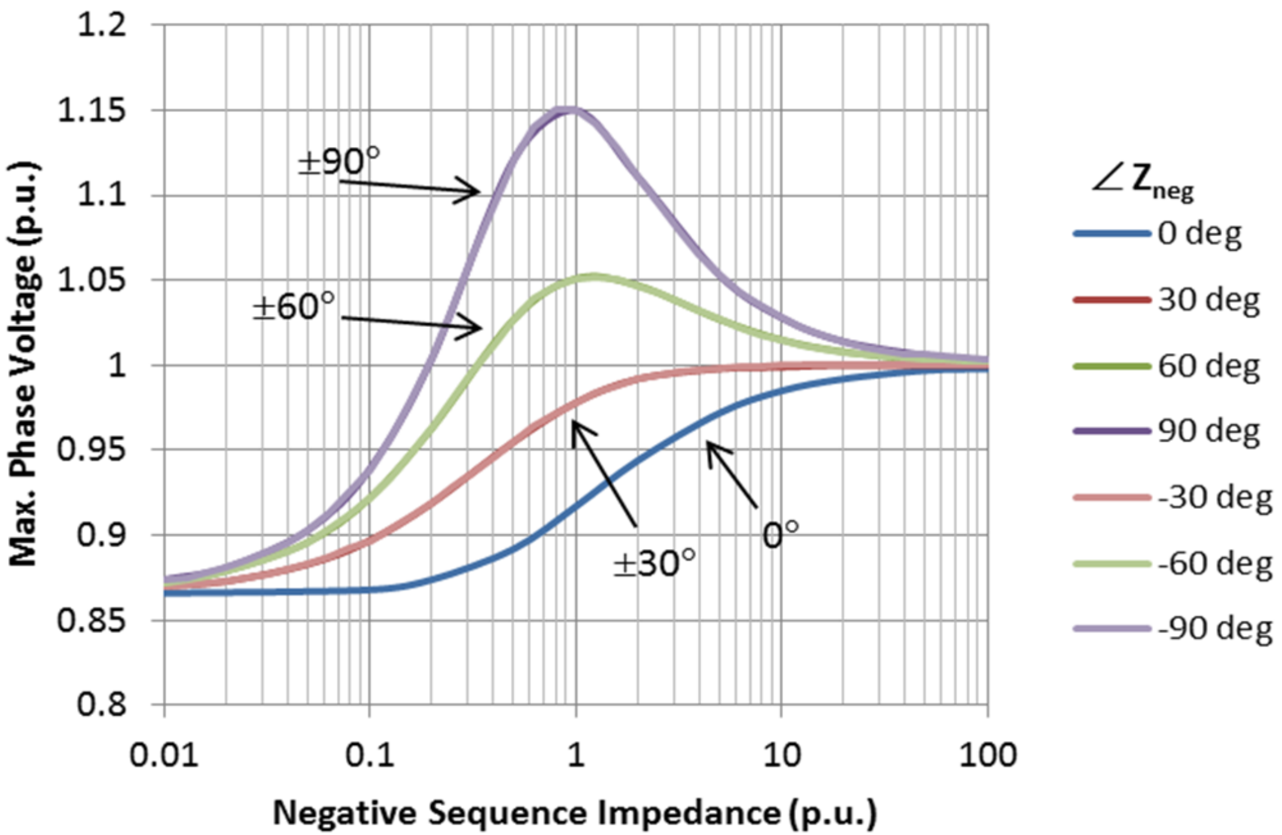
- Inverter sources require a different approach to evaluation of system grounding and application of supplemental ground sources
- Many/most DER interconnections may not need supplemental grounding to be specified
- Where supplemental ground sources are applied, their parameters should be specified considering the nature of the inverter DER sources
- Inappropriate ground sources or ground source parameters can have significant adverse system impact

BACKUP
Impact of Inverter Negative Sequence Characteristics

Inverter Negative Sequence Impedance

- Negative sequence voltage appears as 2^{nd} harmonic in the d-q reference frame
- 120 Hz is within the bandwidth of most inverter current regulators
- Current control tends to “buck out” negative sequence current
- Gain and phase of current regulator at 120 Hz defines the effective $|Z_2|$ and $\angle Z_2$
- Range of Z_2
  - Some references indicate effective Z_2 is quite large
  - Reverse engineering of one test case seems to imply $Z_2 \approx 1$ p.u.
  - Limiting case of a slow current regulator is the physical impedance of the inverter’s output (filter) reactors
- For study, assume 0.01 p.u. $< |Z_2| <$ 100 p.u., and $-30° < \angle Z_2 < 60°$

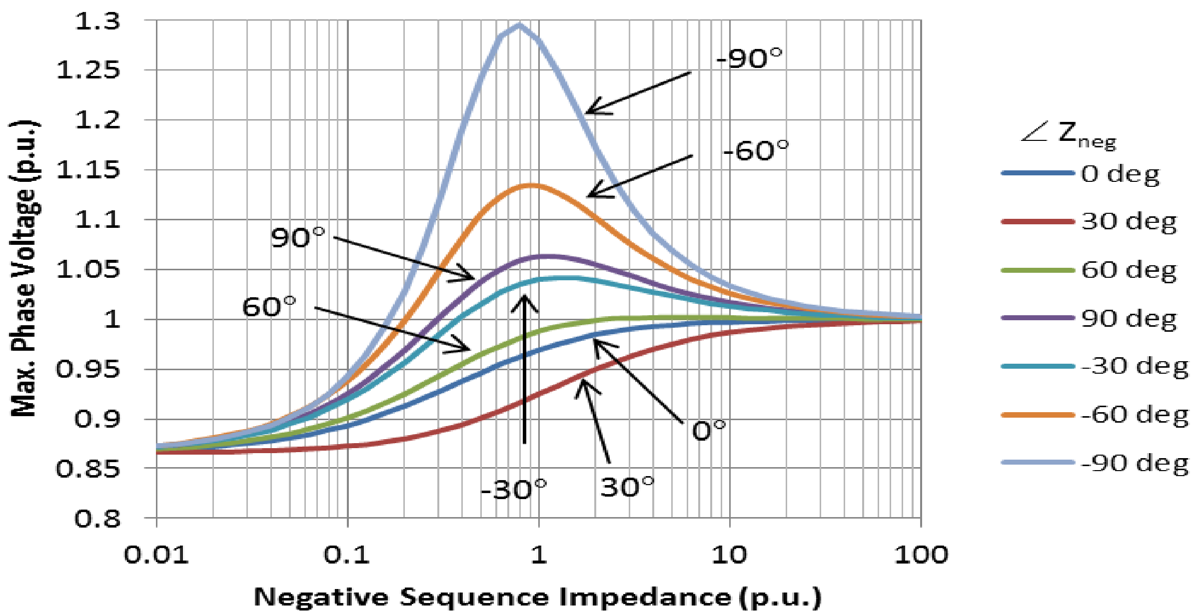
No Ground Source, Current Limit 1.0 p.u., Load pf = 1.0



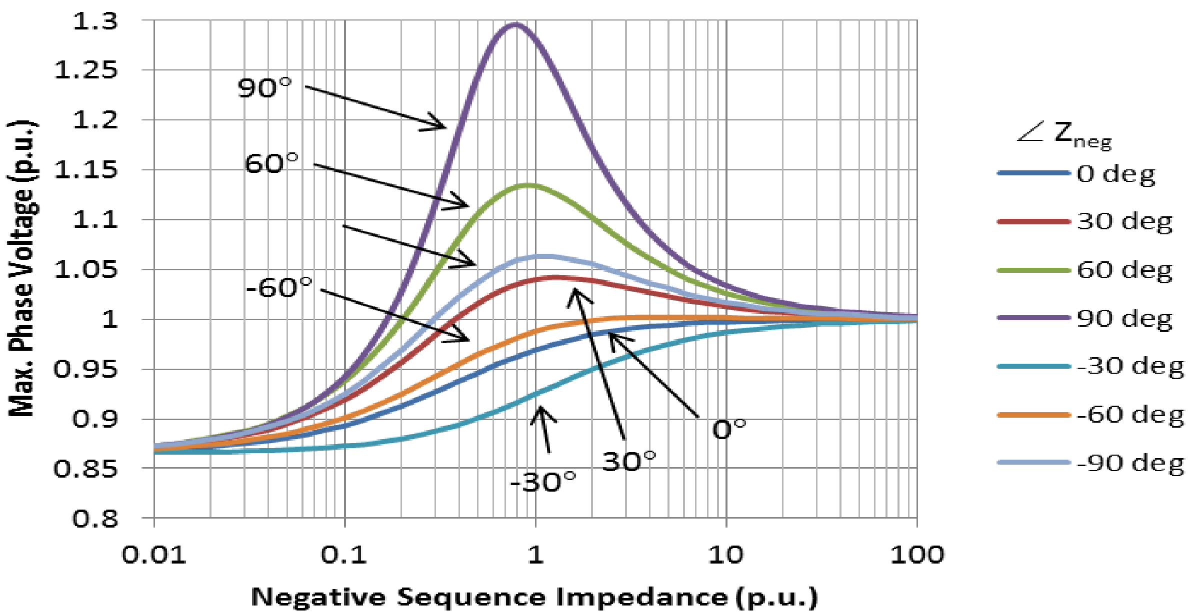
- GFOV is trivial with L-N connected load

No Ground Source, Current limit 1.0 p.u., Load pf = 0.9

Lagging



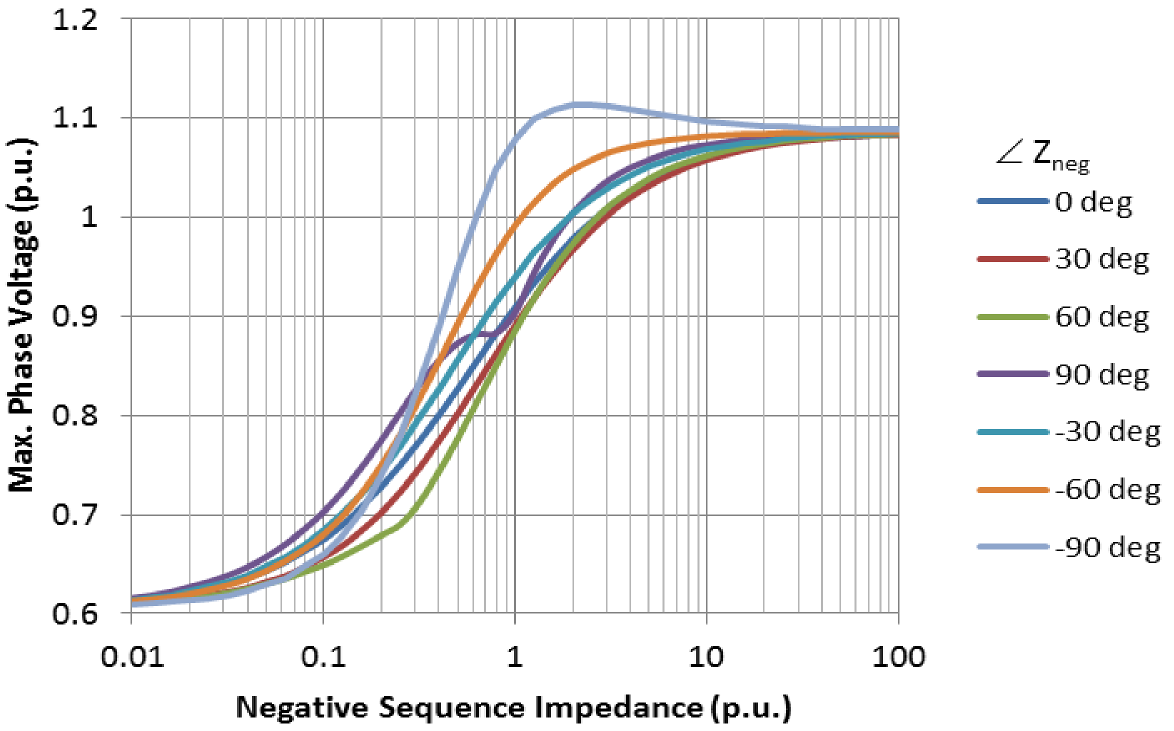
Leading



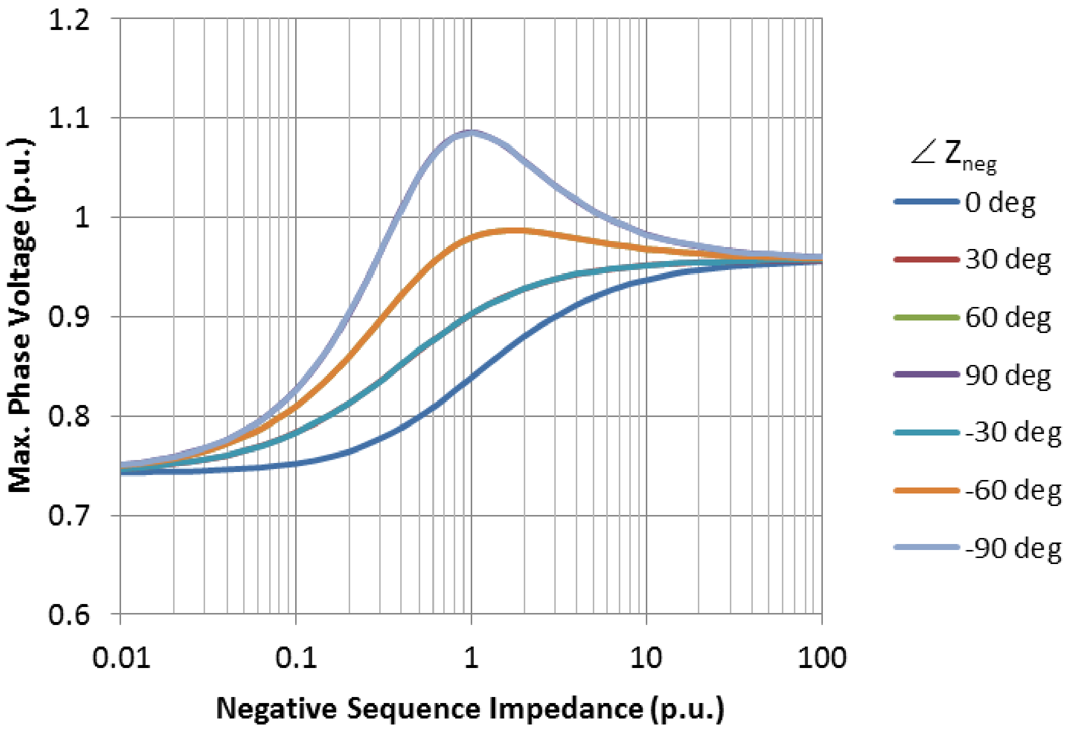
- For the "expected" range of $\angle Z_2$ (-30° → +60°), GFOV is insignificant and relatively insensitive to $|Z_2|$
- Worst case $\angle Z_2$ shifts around with lead vs. lag pf, big picture doesn't change

With Ground Source, Current limit 1.0 p.u., Load pf = 0.9

Z_{GT} = 0.15 + j0.6



Z_{GT} = 3



- Relatively insensitive to $\angle Z_2$
- Sensitive to $|Z_2|$, but GFOV is not significant
- Inductive ground source with high $|Z_2|$ actually makes GFOV worse than with no ground source!

BACKUP
Partial Load DER Operation Prior to Ground Fault

Pre-Fault Partial Load Operation

- For constant-current output into a matched load, ground fault will result in total active power ≈ 2/3 × pre-fault active power.
  - Assumes no supplemental ground source is present
  - Assumes inverter $Z_2 \rightarrow \infty$
- Power regulation functions will tend to increase current in order to reach power setpoint
  - Without current limits, resulting unfaulted phase voltage will be approximately:

$$\bar{V}_{unf} \approx \sqrt{\frac{3}{2} \cdot \frac{\bar{P}_{DER}}{\bar{P}_{Load}}}$$

V_{unf} = Unfaulted phase voltage to ground (p.u.)
P_{DER} = DER active power, (p.u. of DER rating)
P_{Load} = Load demand at nominal voltage (p.u. of DER)

  - With current limits:

$$\bar{V}_{unf} \approx \min\left[\sqrt{\frac{3}{2} \cdot \frac{\bar{P}_{DER}}{\bar{P}_{Load}}}, \frac{\bar{I}_{Limit}}{\bar{P}_{Load}}\right]$$

I_{Limit} = Inverter current limit (p.u.)

- At full load, current limit will usually dominate; at partial load GFOV may be higher even with $P_{DER} = P_{load}$
- DER penetration must be greater for $P_{DER} = P_{load}$ to occur at partial DER load

BACKUP
Design Options and Rating Considerations for Supplemental Ground Sources

Providing a Ground Source

Options:

1. Separate grounding transformer (zig-zag or grounded-wye/delta) with grounding resistance
   - Resistance between neutral and ground, for either connection, or
   - Resistance closing an open-delta of a grounded-wye/delta

2. Grounding transformer with no external impedance

3. Grounding resistance between neutral and ground of grounded-wye/delta DER step-up transformers (or zig-zag/wye)

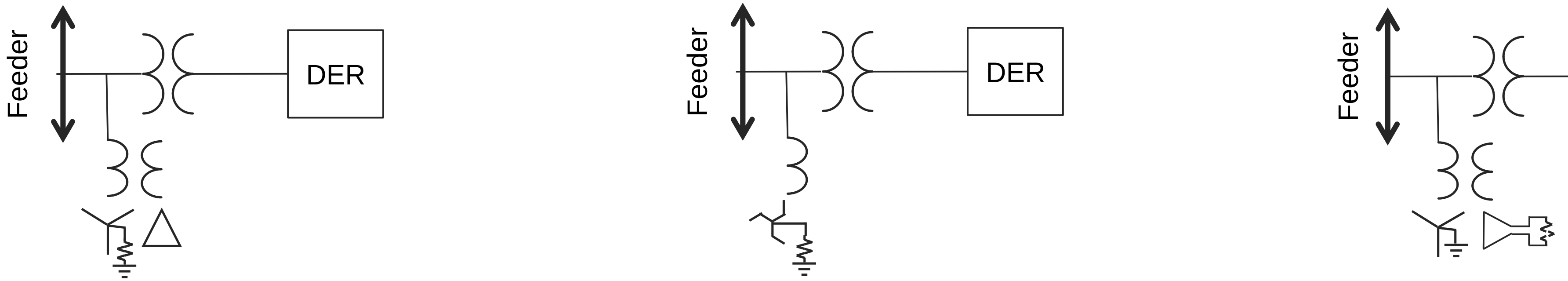
4. Yg/Yg/Delta (3-winding) DER step-up transformers with grounding resistance between utility side neutral and ground

Transformer configurations are illustrated on following slides

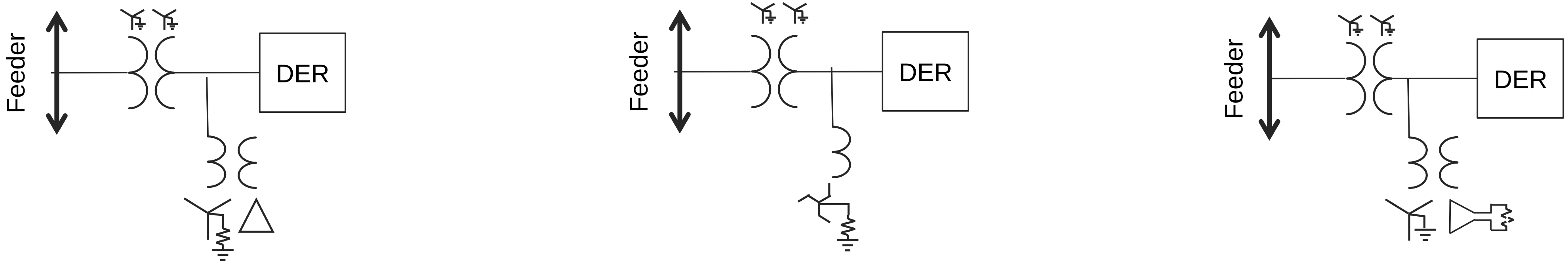
Option #1

Separate Grounding Transformer with Resistance

- Several configurations can be used for this option (step-up transformer should not provide a primary ground source)

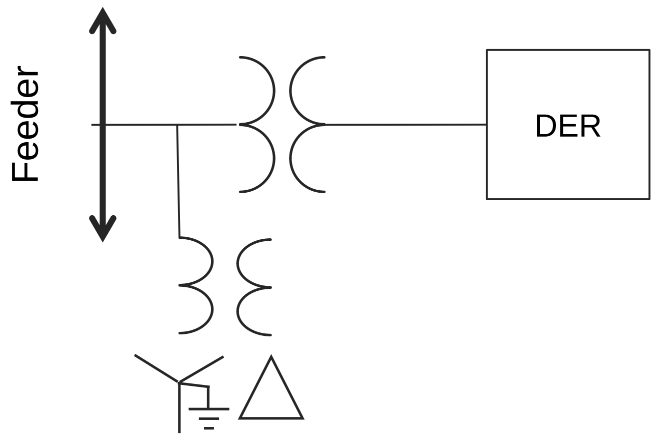


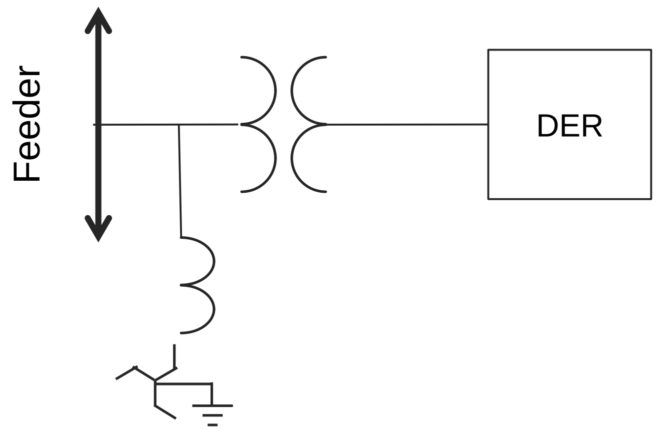
- Note: all of these configurations are effectively equivalent as ground sources; there is no special advantage of zig-zag except that it takes less copper and iron - Tradeoff of a material-efficient special design versus a commodity transformer
- Grounding transformer may also be connected to LV side if the step-up transformer is grounded-wye/grounded-wye
  - Total zero sequence impedance at the primary side sum of the GT and the GSU

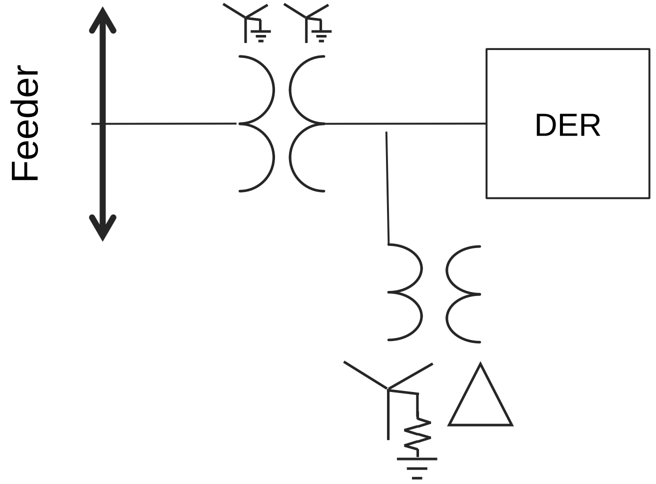


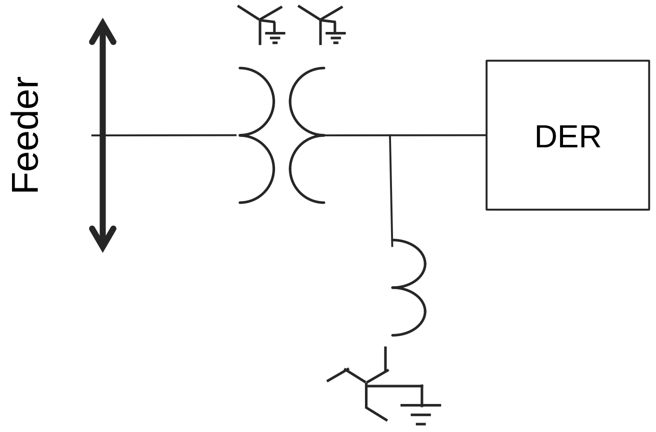
Option #2

Separate Grounding Transformer , no External Impedance



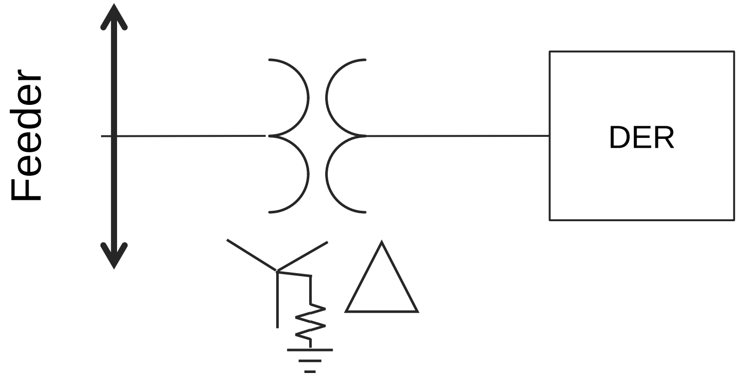


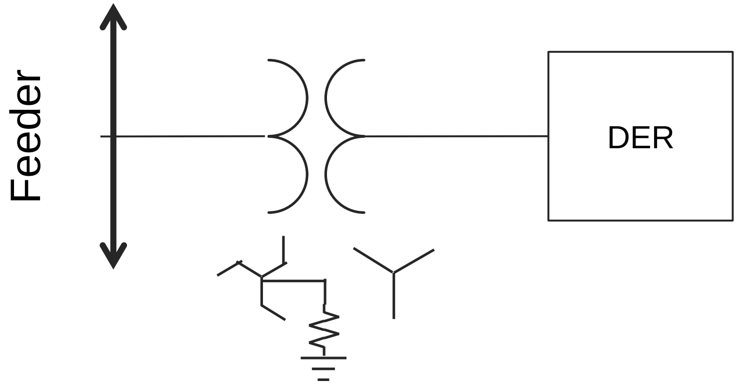




Option #3

Neutral Resistance on Grounded-Wye/Delta GSU (or zig-zag/wye)

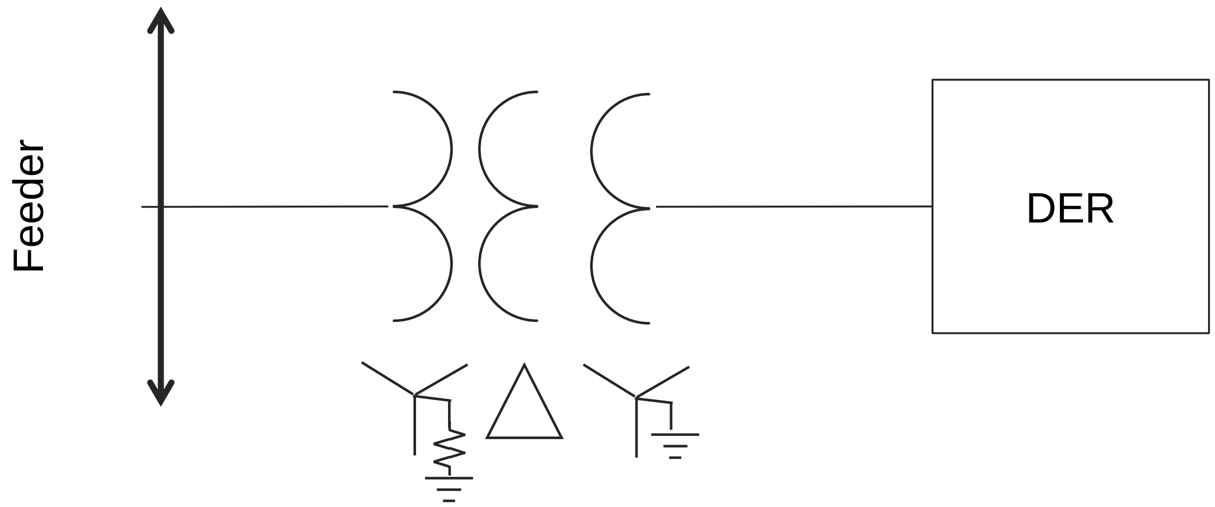




- Zig-zag/wye is an obscure configuration, rarely used

Option #4

Three-Winding GSU with Delta Tertiary and Neutral Resistance on Grounded-Wye



- Provides a ground source to DER side as well as to utility feeder

Ground Source Rating Considerations

Ground fault while feeder is connected to substation (ignore loads and small contribution of inverter)

$$I_{G0} = \frac{V_{LL} \cdot I_{3ph} \cdot \left(3 \cdot I_{3ph} - 2 \cdot I_{1ph}\right)}{3\sqrt{3} \cdot Z_{G0} \cdot I_{3ph}^{2} + 2 \cdot V_{LL} \cdot \left(3 \cdot I_{3ph} - 2 \cdot I_{1ph}\right)}$$

Note: $3 \cdot I_{G0}$ = neutral current ; $Z_{G0}/3$ = neutral impedance

I_{G0} = Ground source zero sequence current
V_{LL} = Line-to-line voltage of utility source
I_{3ph} = Available 3-phase fault current at connection point
I_{1ph} = Available 1-phase fault current at connection point
Z_{G0} = Zero sequence impedance of ground source (ohms)

- Conservative approximation

$$I_{G0} \cong \frac{V_{LL} \cdot I_{3ph} \cdot \left(3 \cdot I_{3ph} - 2 \cdot I_{1ph}\right)}{3\sqrt{3} \cdot Z_{G0} \cdot I_{3ph}^{2}}$$

- For a feeder that is effectively grounded when connected to substation, $I_{1ph} > 0.6 \cdot I_{3ph}$

$$I_{G0} < \frac{0.6 \cdot V_{LL}}{\sqrt{3} \cdot Z_{G0}}$$

- Required minimum transformer rating; duration limited by DER or feeder tripping

$$\frac{S_{xfmr}}{P_{DER}} > \frac{0.6}{Z_{Gpu} \cdot K_{oc}}$$

S_{xfmr} = Transformer VA rating
P_{DER} = DER rating (W)
Z_{Gpu} = Ground source zero sequence impedance on DER base
K_{oc} = Transformer overload factor (fault current / rated current)

Ground Source Rating Considerations

Steady state voltage imbalance

$$I_{SS0} = \frac{V_{LL} \cdot \overline{V}_0}{\sqrt{3} \cdot Z_{G0}}$$

I_{SS0} = Ground source steady-state zero sequence current
V_{LL} = Line-to-line voltage of utility source
$\overline{V}_0$ = Zero sequence voltage imbalance (p.u.)
Z_{G0} = Zero sequence impedance of ground source (ohms)

Note: $3 \cdot I_{SS0}$ = neutral current ; $Z_{G0}/3$ = neutral impedance

- Transformer rating required to sustain steady-state imbalance

$$\frac{S_{xfmr}}{P_{DER}} > \frac{\overline{V}_0}{\overline{Z}_{G0}}$$

$\overline{Z}_{G0}$ = Zero sequence impedance of ground source (p.u.)

Ground source rating considerations

Ground fault while islanded

- Assuming worst case of 100% delta-connected load

$$I_{G0} = \frac{Z_L}{Z_L + \frac{Z_L \cdot Z_2}{Z_L + Z_2} + Z_{G0}} \cdot \bar{I}_{inv} \cdot \frac{P_{DER}}{\sqrt{3} \cdot V_{LL}}$$

Z_L = Load impedance
Z_2 = Inverter negative sequence impedance
I_{inv} = Inverter current (p.u. of power rating)

- Conservatively assume $Z_2 \rightarrow 0$ and $Z_L \rightarrow \infty$

$$I_{G0} = \bar{I}_{inv} \cdot \frac{P_{DER}}{\sqrt{3} \cdot V_{LL}}$$

- Required transformer rating to sustain ground fault while islanded

$$\frac{S_{xfmr}}{P_{DER}} > \frac{\bar{I}_{DER}}{K_{oc}}$$

- This is rarely constraining unless trip is delayed a very long time

Grounding Transformer Impedance Constraints

- Natural reactances of medium-voltage transformers in the kVA range appropriate for use as separate grounding transformers tend to be in the 1.5% - 2.5% range
  - Smaller reactance requires special construction; e.g. interleaving of windings
  - Larger reactance requires taller winding and/or more primary-secondary gap space
  - Special designs are inherently more costly and less available than standard designs
- Separate grounding transformer rating selected to yield a given p.u. reactance on DER base is inadequate to sustain short-circuit without:
  - An unnatural reactance, or
  - An external impedance (resistance preferred)
- A Yg-Δ DER step-up transformer will have a reactance of 6% (for large DER facilities > 500 kW), less for smaller DER
  - Current for feeder ground fault (feeder connected to substation) is 10 x rating
  - Per IEEE C57.109, transformer can withstand this current for 10 seconds for “frequent occurrence”
  - Large adverse impact on feeder ground protection and arc flash hazards – too strong a source
  - Adding a neutral resistor is desirable to weaken source
- Impedance from feeder side to delta tertiary is the critical parameter for Yg-yg- Δ three-winding DER step-up transformers
  - Depends on transformer design, as does the rating of the delta tertiary winding

BACKUP
Supplemental Ground Optimization Case Study

Additional assumptions for example comparison

- Grounding transformer steady-state duty base on 4% zero-sequence voltage
- Grounding transformer short-term duty based on ground fault at PCC
- Grounding transformer rating based on 10 x overload factor, assuming 10 second backup clearing time
- Standard transformer kVA ratings assumed for grounding transformers
  - Assumes ordinary distribution transformers (Yg-Δ) used instead of custom zig-zag grounding transformers
  - Custom grounding transformers can be designed for actual current requirements
  - Optimization of custom design yields a more efficient design (less material)
  - Tradeoff of cost for customized special transformer vs. larger commodity unit is case-by-case dependent
- GFOV evaluation based on $P_{load} = P_{DER}$, load at 0.95 leading power factor
- Inverter current limited to 1.1 p.u. of rating

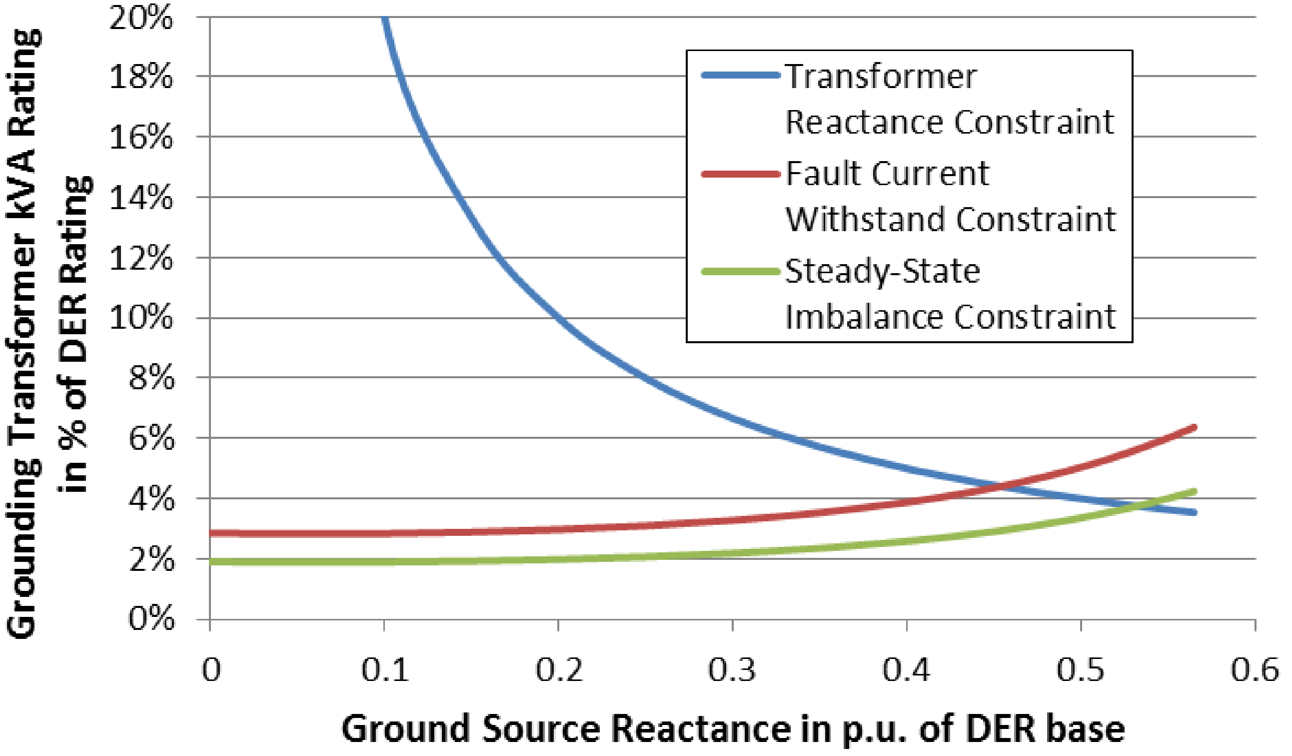
Ground source optimization and design

Option #1 – Separate grounding transformer and neutral resistance

- Constraining factors for transformer kVA rating:
  - kVA rating to provide the given reactance on DER base
  - kVA rating required to withstand feeder-connected fault current
  - kVA rating to withstand steady-state imbalance current (typically non-critical)
- Plot shows optimization; least required kVA is where reactance and fault constraint lines cross →
  - Assumptions:

    2% reactance on transformer's own base

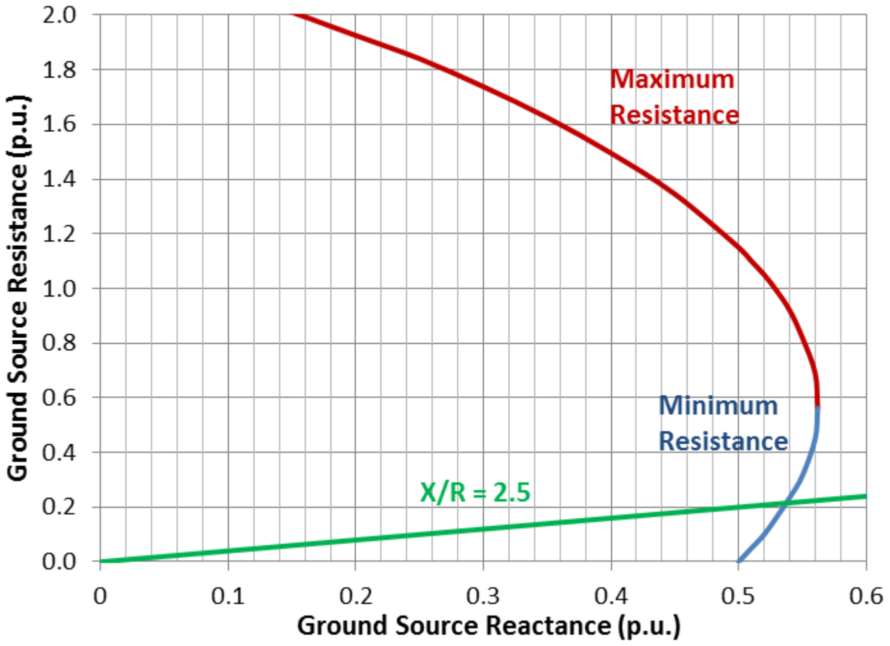
    10 x overcurrent allowable for fault
- Optimum reactance is ~0.45 p.u. on DER base for these assumptions
  - Transformer kVA rating = 4.44% of DER
  - Additional resistor to provide total of 1.31 p.u. Zero sequence resistance on DER base (need to account for transformer's resistance)



Ground source optimization and design

Option #2 – Separate grounding transformer without added impedance

- Largest reactance to provide effective grounding yields least transformer kVA rating
  - From earlier slide, largest reactance is 0.565 p.u. on DER base
  - Requires that resistance also be 0.565 p.u. ,
    or X/R = 1; less than typical for transformers > 100 kVA
  - Typical X/R for transformers in this size range is ~2.5
- Intersection of X/R line and minimum resistance curve indicates reactance of 0.54 and resistance of 0.216 p.u. on DER base
- Required transformer rating to withstand fault current (assuming 10 x overload factor) is 10.3% of DER rating



$$\frac{S_{xfmr}}{P_{DER}} > \frac{0.6}{Z_{Gpu} \cdot K_{oc}} = \frac{0.6}{\sqrt{0.216^2 + 0.54^2} \cdot 10} = 0.103$$

- Transformer's reactance on own base is 0.103 × 0.54 = 0.0557
  - Feasible, but it is a special design for transformers < 750 kVA

Ground source optimization and design

Option #3 – Neutral resistance added to two-winding step-up transformer

- Step-up transformer must have either
  - A grounded-wye connection on feeder side and a delta winding on the DER side, or
  - A zig-zag winding connection on the feeder side and any connection on DER side (rarely used option)
- Zero sequence shunt reactance (ground source) is 6% or less on DER base
- Small reactance allows use of a much larger resistance
  - Figure on prior slide shows resistance < 2.15 p.u. can be used
- Large resistance reduces fault current
  - Fault current is less than transformer's rated current; can withstand indefinitely
  - Reduces adverse impacts of a ground source on a feeder
- Large resistance reduces neutral resistor rating
  - Short-term rating in kJ
  - Steady-state rating in kW

Ground source optimization and design

Option #4 – Neutral resistance added to three-winding step-up transformer

- Step-up transformer must have a grounded-wye connection on feeder side and a delta tertiary winding
  - DER-side winding can be any connection
- If DER-side transformer is grounded-wye, there will be (limited) zero-sequence continuity
  - Inverter can "see" GFOV to some extent
  - Percentage of feeder-side zero sequence voltage seen at the inverter depends on the transformer impedances and the neutral impedance.
- Tertiary typically does not have the full rating of the main windings
  - Impedance to tertiary (Z_{HY}) is dependent on tertiary rating
- Tradeoffs between tertiary rating, ground source impedance, and transformer impedances are somewhat complex and get into the transformer internal design factors
  - Three-winding transformers are a very specialized item

BACKUP
Modeling Tools

Modeling Tools for GFOV Analysis

- The analysis shown in this presentation was performed using fundamental symmetrical component analysis in a general purpose mathematical software (MathCAD)
  - Allows full flexibility and control of modeling
- Utilities will tend to do this type of analysis using short-circuit software
- The representation of inverter sources in the popular software was investigated
  - General purpose short-circuit analysis software (Aspen and CAPE)
    - Primary focus of inverter model development was to model transmission-connected wind plants
    - Voltage-defined positive sequence current source to represent "fault ride-through" mode required by European standards, initially for wind plants, now for MV-connected DER as well. Current phase angle is a function of voltage
    - Negative sequence modeled to be open circuit
  - Distribution-specific software (Synergi and Cyme)
    - Simple positive sequence current source
    - Negative sequence assumed to be modeled as an open circuit
  - These tools provide reasonably good capability to model GFOV if:
    - No "FRT" mode is used; this is not typical of DER inverters
    - Loads are properly modeled
    - No cases have voltage across the inverter (L-N or L-L) substantially greater than nominal
    - Lack of negative sequence modeling is a deficiency, but impacts on results are generally not extreme

Together…Shaping the Future of Electricity