Sizing of and ground potential rise calculations for grounding transformers for photovoltaic plants

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Special thanks to:
• Tom Yohn, Xcel Energy
• Marc Johnson, Johnson and Associates Engineering LLC
• Michael Beanland, TriAxis Engineering
• Matthew Charles, Advanced Energy
• Lou Gasper, Gerlicher Solar
Part 1

Design of grounding transformers for PV plants
Debate over effective grounding of PV plants

- There is considerable discussion as to whether effective grounding of PV plants is really necessary.
  - Intent: prevent Ground Fault Overvoltage (GFO)
  - Issue: properly-operating PV inverters do not reinforce GFO
  - Status: discussion ongoing

- Until this issue is settled, many utilities are requiring grounding transformers on PV plants.

- In some circumstances (mostly delta load, delta-Yg GSU transformer), a grounding transformer may be needed anyway.
Purpose of this presentation

• Conventional method of grounding transformer design (IEEE 142) wasn’t designed for inverters.
  • Inverter “impedances” are software defined; hard to come up with values
  • Equivalent impedance is primarily resistive
  • Often the resulting transformer impedance is very low

• This presentation proposes an alternative procedure for use with PV plants that:
  • Works
  • Is simple
  • Requires minimum data inputs from the host utility
  • Produces results that are conservative but not excessively costly
Sequence networks during SLG fault

- PV is a positive-sequence current source
- Grounding tx shown
- If no grounding tx, zero sequence path provided by:
  - Loads
  - Arrestors
  - Charging capacitance
Designing the grounding transformer

• The grounding transformer designer must specify six electrical parameters:
  • Terminal voltage
  • Zero-sequence fault current
  • Duration of zero-sequence fault current
  • Continuous zero-sequence current (circulating current)
  • Zero-sequence $R_g$ and $X_g$

• There are several non-electrical parameters too, of course (termination types, packaging, etc.).
Grounding transformer impedance selection

- The grounding transformer’s purpose is to provide the zero-sequence impedance that limits GFO to some acceptable level (usually taken to be 1.2 pu).

- We use the impedance recommendation made in IEEE 1547.8. The grounding transformer $X_g$ and $R_g$ are set according to:

$$Z_{base,PV} = \frac{V_{PV}^2}{S_{PV}} \quad \Rightarrow \quad X_g = 0.6 \times Z_{base,PV} \quad \Rightarrow \quad \frac{X_g}{R_g} \geq 4$$
Basis for values

• The $X_g = 60\%$ of $Z_{\text{base,PV}}$ value holds the voltage to 1 p.u. in a case in which the inverter is supplying 1.67 pu fault current in steady state (i.e., this is sort of the synchronous impedance of the inverter). This is VERY conservative.

• The $X_g/R_g$ ratio is then set so that at the maximum value of $R_g$, the TOV is still kept below 1.2 pu.

• This transformer impedance is also supposed to help with the problem of desensitizing protection.
Calculation of the steady-state circulating current

• Circulating currents result primarily from steady-state phase-phase voltage imbalance.

• Approach: find the zero-sequence voltage $V_{a0}$ across the grounding transformer impedance as a function of imbalance.

• Then, the required circulating current rating is found from Ohm’s Law.
Calculation of the steady-state circulating current

• First, allow $x$ and $y$ to be the magnitudes of the phase B and C voltages relative to the phase A voltage, as seen at the grounding transformer terminals.

• We can then express the unbalanced phase voltages this way:

$$V_b = ax \cdot V_a$$
$$V_c = a^2 y \cdot V_a$$

(Here $a$ is the 120° phase shift operator and $a^2$ is 240°)
Calculation of the steady-state circulating current

• Sequence components:

\[
\begin{bmatrix}
V_{a0} \\
V_{a1} \\
V_{a2}
\end{bmatrix} = \frac{1}{3} \begin{bmatrix}
1 & 1 & 1 \\
1 & a & a^2 \\
1 & a^2 & a
\end{bmatrix} \times \begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
\]

• Sub in for \(V_b\) and \(V_c\) in terms of \(x\) and \(y\), and find \(V_{a0}\):

\[
V_{a0} = \frac{V_a}{3} \cdot (1 + ax + a^2y)
\]
Calculation of the steady-state circulating current

- Sub in rectangular expressions for $a$ and $a^2$:

$$V_{a0} = \frac{V_{a1}}{3} \left( 1 + x \left[ -\frac{1}{2} + j\frac{\sqrt{3}}{2} \right] + y \left[ -\frac{1}{2} - j\frac{\sqrt{3}}{2} \right] \right)$$

- Now, a simplification—assume the percent imbalance $P$ is symmetrical, so that $x$ and $y$ are functions of $P$:

$$x = 1 + \frac{P}{2} \quad y = 1 - \frac{P}{2}$$
Calculation of the steady-state circulating current

• Sub in for $x$ and $y$ in terms of $P$ and simplify, and we get:

$$V_{a0} = j\frac{\sqrt{3}}{6} \cdot PV_{a1}$$

• Then, the magnitude of the circulating current in the grounding tx, $I_g'$, is:

$$I_g' = \frac{\sqrt{3}PV_{a1}}{6Z_g} = \frac{PV_{a1}}{2\sqrt{3}Z_g}$$
Calculating the steady-state circulating current

• How well does this approximation work? Turns out, it needs adjustment. Two main reasons:
  • Asymmetry in the imbalance
  • Not quite 120° of phase separation
Calculation of the steady-state circulating current

• Could go with the full expression...

\[ V_{a0} = \frac{V_{a1}}{3} \cdot [1 + x(\cos \theta_b + j \sin \theta_b) + y(\cos \theta_c + j \sin \theta_c)] \]

• ...but in the planning/design phase we generally do not know x, y, or any of the \( \theta \) values.
Calculation of the steady-state circulating current

• Thus, the approach we have taken here is to be excessively conservative and simply double the value given by the approximate expression:

\[ I'_g = \frac{PV_{a1}}{\sqrt{3}Z_g} \]

• This value will result in a design with good margin but without excessively raising transformer cost.
Calculation of the fault current withstand rating

• Fault current duration is usually taken to be 2 sec (represents worst-case time to trip).

• For fault current magnitude, plan of attack is essentially the same as before—find the worst-case zero-sequence voltage, then use Ohm’s Law and the known transformer impedance to find the current.

• What is the worst-case zero sequence voltage during an SLG fault?
Theoretical absolute worst case would be with all positive and negative sequence impedances set to zero (no impedance divider; 100% of $V_{a1}$ appears across $Z_{0,g}$).
Calculation of the fault current withstand rating

• Thus, we choose the following expression for the fault current withstand rating:

\[ I_g = \frac{V_{a1}}{Z_g} \]

• Again, this gives a conservative but not excessive specification.
• The grounding transformer is now fully specified.
Practical notes regarding selecting a grounding transformer

- The good news is that this procedure results in small (low-cost) grounding transformers.
- The bad news is that in that smaller size range, the $X_g/R_g$ ratio tends to drop and it can become difficult to maintain $X_g/R_g \geq 4$.
- If a compromise is required, be sure to maintain the correct impedance, then overdesign the current ratings until the desired $X/R$ can be maintained.
- Don’t forget to include a tolerance.
Quick note regarding LRO vs. GFO

• We have been specifying a grounding transformer to mitigate ground-fault overvoltage (GFO).

• One may also consider load rejection overvoltage (LRO), which can occur if large generation is isolated with small load.

• **Grounding transformers generally do not mitigate LRO**; if the load is reasonably well-balanced, LRO is primarily a positive-sequence phenomenon and is relatively unaffected by effective grounding.
Part 2

Calculation of ground potential rise for PV plants with grounding transformers
Ground Potential Rise calculations

• Sometimes when a grounding transformer is used, it is also necessary to calculate the expected level of Ground Potential Rise (GPR) during a fault.

• This is especially true if copper-based communications channels to the site are employed. GPR at one end of a copper communications link can lead to equipment damage.

• Usual approach: apply IEEE Std 367.
A cautionary note about GPR calculations

• However, it is common practice to use the utility’s usual fault current calculation as the starting current for the IEEE 367 calculation.

• That usual fault current calculation assumes the impedance to remote earth is zero, which would by definition give a GPR of zero.
  • This practice has sometimes led to calculated GPR values higher than the phase-phase line voltage.

• Need a means for finding the fault current that does include the impedance to remote earth.

• Suggestion: include these impedances in the sequence networks.
System configuration for GPR calculation
Sequence networks

$R_{PVgnd}$ and $R_{subgnd}$ are the PV plant and substation (respectively) impedances to remote earth, and $Z_{neut0}$ is the impedance of the neutral.

Normally, $R_{Fgnd}$ and $Z_F$ would both still be set to zero.
Unfortunately the resulting closed-form expression for the fault current is cumbersome, because the zero-sequence network forms a Wheatstone bridge.

This is more conveniently solved using PSpice or another circuit solver.
Note on the GSU transformer

- Most GSU transformers have their H and X side neutrals connected.
- In this case, make sure the GSU transformer zero-sequence impedance is properly calculated. From the old Westinghouse book:

\[
Z_{x0} = Z_{x1} + 3 \frac{(N - 1)^2}{N^2} Z_G \\
\approx Z_T + 3Z_G
\]
Testing of the sequence network representation
Testing of the sequence network representation

Results from the detailed transient model were compared against results from the modified sequence network model.

<table>
<thead>
<tr>
<th>Case description</th>
<th>Detailed model result (Vrms)</th>
<th>Seq net model result (Vrms)</th>
<th>Percent error</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV-side fault</td>
<td>272.2</td>
<td>271.8</td>
<td>-0.15%</td>
</tr>
<tr>
<td>MV side fault</td>
<td>38.7</td>
<td>38.0</td>
<td>1.81%</td>
</tr>
</tbody>
</table>
Conclusions

• A design/specification procedure for grounding transformers for PV plants has been proposed. This procedure:
  • Is simple
  • Leads to a reasonable yet conservative design
  • Requires only minimal data from the utility

• If one must calculate GPR for a PV plant with a grounding transformer:
  • Use fault currents that were calculated properly including the resistances to remote earth
  • Make sure the GSU transformer impedance is properly handled
Thank you!

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