PV and Inverter-based DER Ground Referencing Requirements and Sample Calculations

Scope

This document lists technical requirements, and provides sample calculations, for ground referencing of inverter based Distributed Energy Resources (DER) on Xcel Energy's 4-wire system medium-voltage (MV) electric distribution system. DER units with AC nameplate capacities from 100kW to 10MW are covered in the scope. This document assumes a proper ground reference is being created by either a separate grounding transformer or a wye-grounded:delta (MV:LV) interconnection transformer. Inverters which have an internal grounded-wye isolation transformer are not covered in this document. The information in this document is to be applied at the Point of Common Coupling.

Background

Ground referencing electric distribution systems is standard practice in large part to avoid damaging overvoltages, for line-to-ground connected loads, which can result from ground fault conditions on ungrounded systems. Figure A below shows the range of expected line voltages for different system ground referencing methods. Line surge arrestors and customer equipment connected phase-to-ground are usually not designed to withstand the phase-to-phase voltages that can occur during ungrounded system fault conditions.

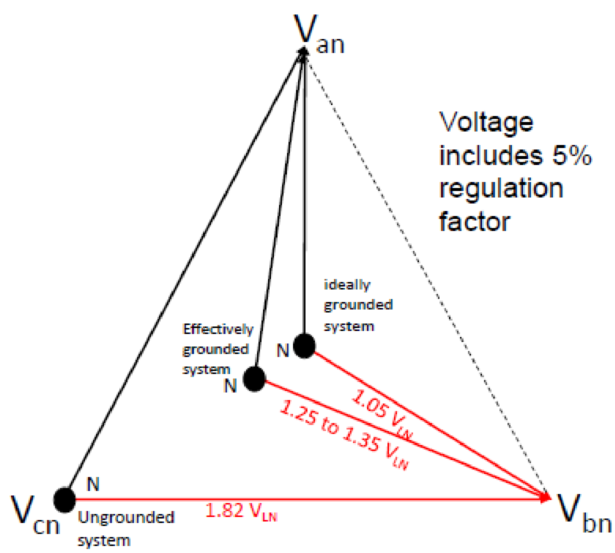

Figure A – Neutral shift during ground fault conditions

During a ground fault condition, in situations where the Xcel Energy's protective device opens and before the DER trips off-line, the distribution system has lost the system ground reference. It is important that any DER source energizing this portion of the distribution system provides a ground reference in order to prevent overvoltages.

Std IEEE 1547-2003 states that "the grounding scheme of the DR interconnection shall not cause overvoltages that exceed the rating of the equipment connected to the Area EPS". The below requirements for inverter ground referencing are adopted from IEEE P1547.8/D8-2014 which is the draft document titled *Draft Recommended Practice for Establishing Methods and Procedures that Provide Supplemental Support for Implementation Strategies for Expanded use of IEEE Standard 1547.* Although this document as a whole is in draft form and not yet approved, Xcel Energy believes the provision below on inverter ground referencing identifies a best practice.

Requirements

For DG Facilities with an Inverter Interface:

1.) $X_{0,DG} = 0.6\, p.u \pm 10\%$ Note: 1 p.u. is based on $Z_{Base} = \frac{kV^2}{MVA_{DER}}$

2.) $\frac{X_{0,DG}}{R_{0,DG}} \geq 4$

3) Ground referencing equipment shall be designed to withstand a minimum of $V_0 = 4\%$ and remain connected

Note: I_0 can be approximated as $I_0 = \frac{V_0}{Z_0}$

4) Ground referencing equipment shall have 5-second withstand ratings that exceed maximum available short-circuit current for close in faults

Additional Notes:

a) Sum of MVA ratings of DER inverter nameplates and high-side (medium voltage) kV rating of interconnection transformer or grounding bank, depending on which unit creates the ground source, are used in determining required zero-sequence impedance ($X_{0,DG}$) for composite facility

b) The MVA and high-side kV rating of the interconnection transformer or grounding bank, depending on which unit creates the ground source, is used for determining grounding bank and neutral reactor sizing

c) The impedance of the interconnection transformer is needed for neutral reactor sizing

Example Calculations

The below examples assume a ground reference is created by a proper transformer configuration and that the PV facility is interconnected to Xcel Energy's 4-wire electric distribution system. For simplicity, the example online diagrams below exclude system components not relevant to grounding requirements; these drawings are not intended to be used as example onelines for system design.

<u>Example 1 – Separate Zig-Zag Grounding Transformer</u>

A PV facility with 1 MVA inverter total AC nameplate is interconnected to a 13.8kV feeder through a 1 MVA interconnection transformer that does not create a ground reference. A separate zig-zag transformer is connected at 13.8kV to meet ground referencing requirements. (Note: Secondary ground bank connections are also acceptable when the interconnection transformer is wye-grounded:wye-grounded. The kV used for determine Z_{Base} would be 480V in that case.)

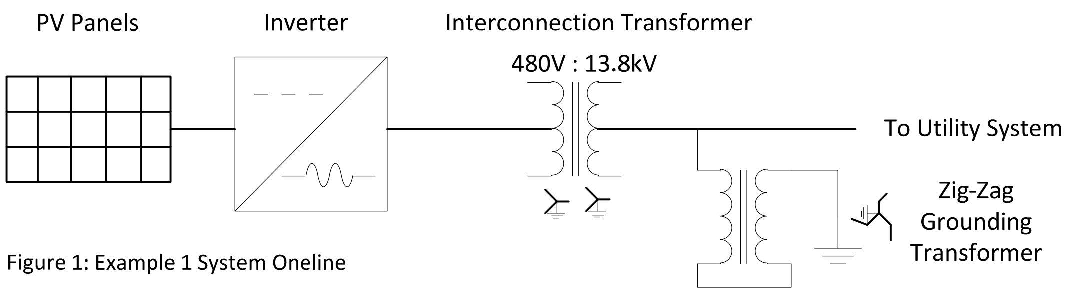

Figure 1: Example 1 System Oneline

i) Find base impedance:

$$Z_{Base} = \frac{kV^2}{MVA_{PV}} = \frac{13.8^2\ kV}{1\ MVA} = 190\ \Omega$$

Notes: kV is high-side voltage of grounding transformer. MVA_{PV} is aggregate facility (i.e. 5 MVA would be used for five 1 MVA facilities)

Find zero-sequence reactance requirement:

$$X_{0,DG} = 0.6(190)\Omega\ \pm 10\% = 114\ \Omega\ \pm 10\%$$

The zig-zag grounding transformer will require a per phase zero-sequence reactance of $114\ \Omega\ \pm 10\%$ to meet Requirement 1.

ii) For Requirements 2, verify $\frac{X_{0,DG}}{R_{0,DG}} \geq 4$

iii) For Requirement 3, assuming $X_{0,DG} = 114\ \Omega$ determines the continuous current associate with $V_0 = 4\%$.

Find base current value

$$I_{Base} = \frac{V_{Base}}{Z_{Base}} = \frac{\frac{13.8}{\sqrt{3}}kV}{190\ \Omega} = 41.8\ A$$

Find per unit zero sequence current

$$I_{0,p.u} = \frac{V_0}{Z_0} = \frac{0.04}{0.6} = 0.067\ p.u.$$

Find zero sequence current in amps

$$I_0 = I_{Base} * \ I_{0,p.u} = 41.8\ A * 0.067 = 2.8\ A$$

Verify that the transformer per phase rating exceeds this value.

Find neutral current

$I_N = 3(I_0) = 3(2.8)\ A = 8.4\ A$

Verify that the transformer continuous neutral rating exceeds this value.

iv) For Requirement 4, request system impedance from the Area engineer and determine ground bank's short circuit contribution for close-in single-line-to-ground faults. The grounding transformer 5-second withstand rating shall exceed the maximum anticipated ground fault current contribution from the transformer.

Example 2 – Wye-grounded:Delta Interconnection Transformer with Neutral Reactor

A PV facility with 1 MVA inverter total AC nameplate is interconnected to a 13.8kV feeder through a 1 MVA interconnection transformer through a wye-grounded:delta interconnection transformer (grounded-wye winding is connected to 13.8kV system). The interconnection transformer has nameplate impedance of 5%. A neutral reactor is required to meet ground referencing requirements.

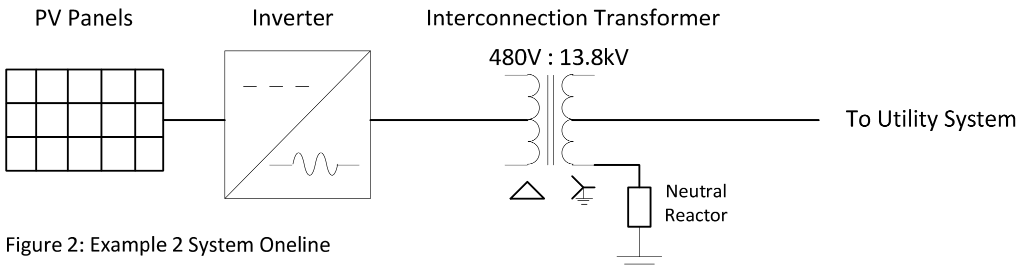

Figure 2: Example 2 System Oneline

i) Find base impedance:

$$Z_{Base} = \frac{kV^2}{MVA_{PV}} = \frac{13.8^2\ kV}{1\ MVA} = 190\ \Omega$$

Notes: kV is high-side voltage of grounding transformer. MVA_{PV} is aggregate facility (i.e. 5 MVA would be used for five 1 MVA facilities)

Find zero-sequence reactance requirement:

$$X_{0,DG} = 0.6(190)\Omega \pm 10\% = 114\ \Omega \pm 10\%$$

Find interconnection zero-sequence reactance contribution:

$$X_{0,Xfmr} = X_{0,Xfmr,pu} * Z_{Base} = 0.05(190)\Omega = 9.5\ \Omega$$

Find neutral reactor zero-sequence contribution to meet requirement by subtracting interconnection transformer contribution:

$$X_{0,NR} = X_{0,DG} - X_{0,Xfmr} = 114 - 9.5\ \Omega = 104.5\ \Omega \pm 10\%$$

Determine neutral reactor size (note: $I_{Nuetral} = 3 * I_{0,Xfmr}$):

$$X_{NR} = \frac{X_{0,NR}}{3} = \frac{104.5\ \Omega}{3} = 34.8\ \Omega \pm 10\%$$

A neutral reactor with reactance of 34.8 Ω ± 10%, inserted into the neutral of the interconnection transformer, will meet ground referencing Requirement 1. Requirements 2 through 4 should be checked using transformer nameplate information.

ii) For Requirements 2, verify $\frac{X_{0,DG}}{R_{0,DG}} \geq 4$

iii) For Requirement 3, assuming $X_{0,DG} = 114\ \Omega$ determines the continuous current associate with $V_0 = 4\%$.

Find base current value

$$I_{Base} = \frac{V_{Base}}{Z_{Base}} = \frac{\frac{13.8}{\sqrt{3}}\,kV}{190\ \Omega} = 41.8\ A$$

Find per unit zero sequence current

$$I_{0,p.u} = \frac{V_0}{Z_0} = \frac{0.04}{0.6} = 0.067\ p.u.$$

Determine zero sequence current in amps

$$I_0 = I_{Base} * \ I_{0,p.u} = 41.8\ A * 0.067 = 2.8\ A$$

Find neutral reactor current

$I_{NR} = 3(I_0) = 3(2.8)\ A = 8.4\ A$

Verify that the neutral reactor continuous rating exceeds this value.

iv) For Requirement 4, request system impedance from the Area engineer and determine ground bank's short circuit contribution for close-in single-line-to-ground faults. The grounding transformer 5-second withstand rating shall exceed the maximum anticipated ground fault current contribution from the transformer.

Example 3 – Separate Wye-grounded:Delta Grounding Transformer

A PV facility with 1 MVA inverter total AC nameplate is interconnected to a 13.8kV feeder through a 1 MVA wye-grounded:wye-grounded interconnection transformer. A separate wye-grounded:delta transformer is connected at 480V to meet ground referencing requirements.

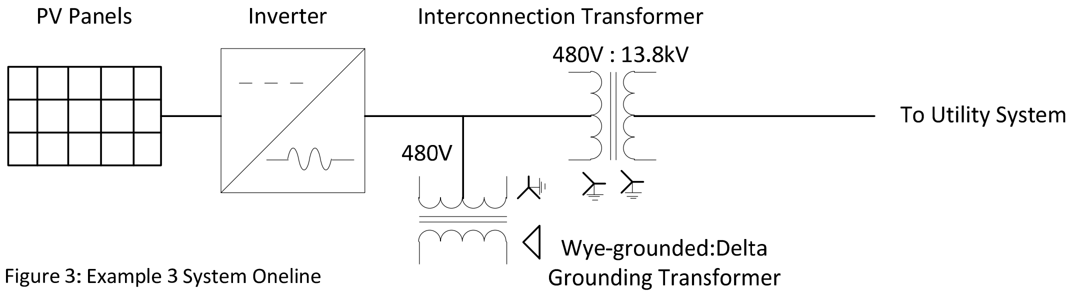

Figure 3: Example 3 System Oneline

i) Find base impedance:

$$Z_{Base} = \frac{kV^2}{MVA_{PV}} = \frac{0.48^2\ kV}{1\ MVA} = 0.2304\ \Omega$$

Notes: kV is high-side voltage of grounding transformer. MVA_{PV} is aggregate facility (i.e. 5 MVA would be used for five 1 MVA facilities)

Find zero-sequence reactance requirement:

$$X_{0,DG} = 0.6(0.23)\Omega\ \pm 10\% = 0.14\ \Omega\ \pm 10\%$$

The grounding transformer will require a per phase zero-sequence reactance of $0.14\ \Omega\ \pm 10\%$ to meet Requirement 1.

ii) For Requirements 2, verify $\frac{X_{0,DG}}{R_{0,DG}} \geq 4$

iii) For Requirement 3, assuming $X_{0,DG} = 0.14\ \Omega$ determines the continuous current associate with $V_0 = 4\%$.

Find base current value

$$I_{Base} = \frac{V_{Base}}{Z_{Base}} = \frac{\frac{0.48}{\sqrt{3}} kV}{0.2304\ \Omega} = 1202.8\ A$$

Find per unit zero sequence current

$$I_{0,p.u} = \frac{V_0}{Z_0} = \frac{0.04}{0.6} = 0.067\ p.u.$$

Find zero sequence current in amps

$$I_0 = I_{Base} * I_{0,p.u} = 1202.8\ A * 0.067 = 80.6\ A$$

Verify that the transformer per phase rating exceeds this value.

Find neutral current

$I_N = 3(I_0) = 3(80.6)\ A = 241.8\ A$

Verify that the transformer continuous neutral rating exceeds this value.

iv) For Requirement 4, refer to the system impedance from the Engineering Scoping Study Results and determine ground bank's short circuit contribution for close-in single-line-to-ground faults. Alternatively this may be requested from Area Engineering. The grounding transformer 5-second withstand rating shall exceed the maximum anticipated ground fault current contribution from the transformer.