**White Paper**
**Effective Grounding for PV Plants**
**SRCW00101**

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# EFFECTIVE GROUNDING FOR PV PLANTS

## I. INTRODUCTION

With the onset of high photovoltaic (PV) penetration, more utility companies are starting to look at PV plants the same way they would look at other major generators. Operational aspects and influence of a PV plant on the distribution network differ from other conventional generators as follows:

- Conventional generators are considered to be voltage sources as they provide constant ac voltages controlled by excitation systems. In contrast, a grid-tied inverter-based PV plant is modeled as a current source whereby the plant's terminal voltage is dependent on the feeder.

- A PV plant is comprised of inverters using power semiconductor switches and microprocessors. Abnormal operation can be detected instantaneously by the control processor and the plant can be protected with response times that are much faster than those of conventional generators. Protective relay functions are built directly into the PV inverter.

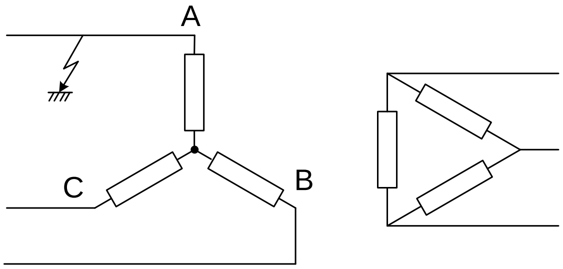
- A PV inverter does not have any mechanical inertia. During a grid fault condition, the inverter short circuit current is equivalent to its rated current and the inverter disables its operation within one or a few cycles.

Due to these inherent characteristics, PV inverters can meet the IEEE 1547 utility interface requirements without the use of external protective relays.

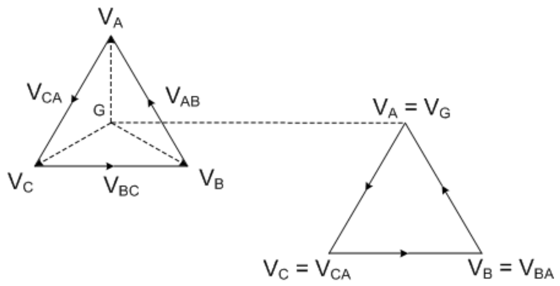
When a PV plant is installed in the distribution feeder, the plant shall meet the IEEE 1547 standard and the interface requirements of the local utility company. Some utility companies require PV inverters to have AC side grounding in order to assure compatibility with their grounding scheme, generally referred to as *effective grounding*. This article explains how grounding is achieved in the distribution network, explains why utilities require effective grounding and elaborates on different fault protection and PV plant grounding schemes. The fault current paths of different transformer configurations are analyzed by means of the sequence network. Throughout this document, the voltage rise in the distribution lines due to line capacitance is ignored.

## II. DISTRIBUTION LINE FAULTS AND GROUNDING

During normal operation, the neutral voltage in a three-phase system is close to zero, regardless of whether the neutral point is tied to the earth ground or not. When a three-phase system with an ungrounded neutral experiences a fault condition, three phase voltages may no longer be balanced; the electrical *virtual neutral voltage* becomes significant, which can cause over-voltage in the phase voltages. A single-line-to-ground fault is the most common fault type in the distribution network, which can generate severe overvoltage conditions and is used to analyze the overvoltage generation as shown in Figure 1.



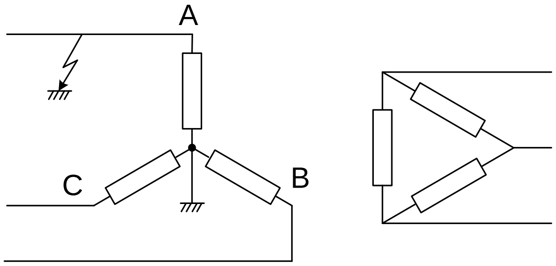
*a) Circuit Configuration*



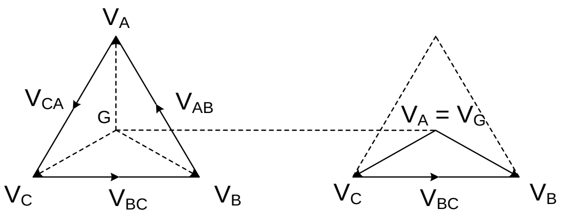
*b) Vector Diagram*

Figure 1. Single-Line-To-Ground Fault on a System with an Ungrounded Transformer

Figure 1 shows a vector diagram of a wye-delta transformer with the neutral ungrounded. Although a wye-to-delta transformer is used here to describe the neutral grounding effect, it also applies to the analysis of conventional rotating generator grounding. Before a fault condition, the three phase voltages are well balanced and the transformer star point voltage is near zero ($V_N = V_G$) as shown on the left side of Figure 1 b). When a single-line-to-ground fault is applied to phase A, phase A becomes grounded and the vector diagram is shifted down as shown on the right side of Figure 1 b). As a consequence, phase B and phase C voltages are increased from line-to-neutral to line-to-line levels. This overvoltage may damage distribution assets and customer loads.



*a) Circuit Configuration*



*b) Vector Diagram*

Figure 2. Single-Line-to-Ground Fault on a System with a Grounded Transformer

Figure 2 shows a similar vector diagram on a solidly grounded system with the same single-line-to-ground fault applied on phase A. The transformer neutral is tied to ground solidly so that the neutral potential cannot change with the fault applied. As a consequence, the phase A voltage vector falls down to the neutral point and the new voltage vector diagram is established as shown on the right side of Figure 2 b). Phase B and C voltage magnitudes remain at their nominal values in contrast to the ungrounded case and no overvoltage is generated.

In North American power distribution systems, the three-phase four-wire multi-grounded system is predominant, which is designed to be less susceptible to the single-line-to-ground fault induced over-voltages described above. In order to maintain overvoltage protection, utility companies require developers to follow their grounding scheme when a new Distributed Energy Resource (DER) is introduced to the network. The purpose of the extension of the grounding scheme to the DERs is to cover the case of an islanded operating condition in combination with a single-line- to-ground fault condition within that island. A grounding bank, to be discussed later, is an equivalent to provide effective grounding and often a preferred alternative due to its flexibility and cost advantage.

## III. EFFECTIVE GROUNDING

Solidly grounding a transformer neutral as shown in Figure 2 eliminates a possible phase overvoltage stemming from a single-line-to-ground fault. A potential problem with the solid grounding in the distribution line is that large fault currents can flow through the transformer neutral, which can desensitize the overcurrent protection coordination. In order to mitigate this issue, impedance grounding can limit the fault current while allowing overvoltage to some limited magnitude. The IEEE green book defines "effective grounding" as the impedance ratios between zero sequence impedance and positive sequence reactance:

$$0 < \frac{X_0}{X_1} < 3, \quad 0 < \frac{R_0}{X_1} < 1 \qquad (1)$$

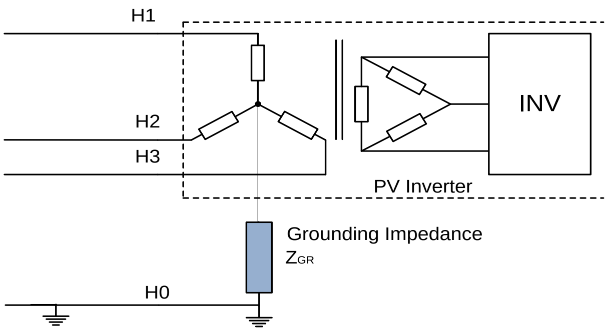
Where
$X_0$: Zero Sequence Reactance
$R_0$: Zero Sequence Resistance
$X_1$: Positive Sequence Reactance

When the above conditions are met for conventional generators, the line-to-ground short circuit current will be limited to 60% of the three phase short circuit value. Also, the overvoltage in the unfaulted phase will be limited to 140% of its nominal value, which is the considered limit of overvoltage without causing equipment damage.

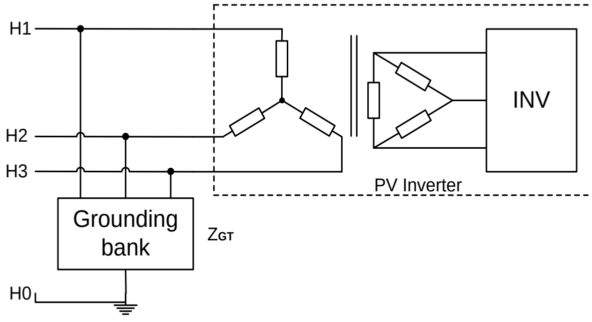
Figure 3 shows two generally accepted effective grounding schemes. When a transformer neutral is available, it can be used to achieve an effective grounding as shown in Figure 3 a). A grounding reactor is used to provide the required $X_0$. If the transformer has a buried neutral or is delta configured, a grounding bank can be used to achieve the same effective grounding, shown in Figure 3 b).

Due to their simplicity and cost effectiveness, grounding banks are widely used to provide effective grounding in three phase three wire systems. A grounding bank uses either a zig-zag or wye-delta transformer which represents a high impedance path for positive sequence voltages but provides a low impedance path for zero sequence voltages. The transformer impedance can be controlled to provide the required effective grounding impedance Xo. If the transformer internal impedance is too small, additional impedance can be added into the grounding bank to achieve the required effective grounding criteria.

For economic purposes, the grounding reactor and the grounding bank are usually rated for short term duty and an overcurrent protection is used to prevent overheating. Figure 4 shows two widely used grounding bank schemes with ground overcurrent protection.



*a) Effective Grounding using Transformer Neutral and a Grounding impedance*



*b) Effective Grounding using a Grounding Bank*

Figure 3. IEEE 142 Suggested Effective Grounding Schemes

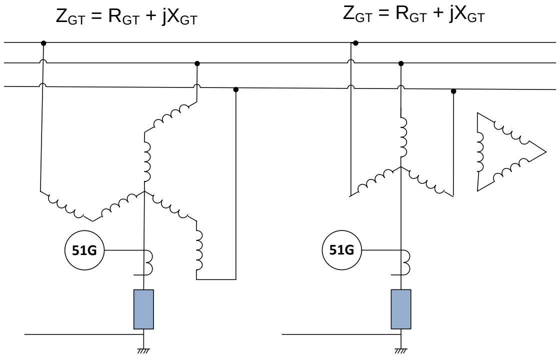


Figure 4. Grounding Bank Configurations: Zig-Zag Transformer (left) and Wye-Delta Transformer (right)

## IV. CONSIDERATIONS FOR PV INVERTER EFFECTIVE GROUNDING

The positive sequence reactance of a synchronous generator is defined by the generator inductance. The use of the inductance value to calculate the positive sequence impedance is straight-forward, see equation (1). In contrast, there is no standard definition of the output impedance of an inverter based DER that industry agrees upon. Some manufacturers use virtual impedance derived from the rated voltage and the measured maximum output current during a fault condition. Others use the physical reactance composed of the output filter inductor and internal transformer leakage impedance, which is usually much smaller than the typical synchronous generator positive sequence impedance of the same capacity. If this small positive sequence reactance ($X_1$) of inverter based DER is used to calculate the zero sequence reactance ($X_0$), there is a risk that distribution feeder overcurrent protection will be desensitized. While many utilities still use the conventional definition for effective grounding, some progressive utility companies used their own guidelines to calculate the required zero sequence reactance for inverter based DER.

Furthermore, there are fundamental debates over whether the effective grounding should be required in the first place for inverter based DERs. This question is related to how inverters are modeled during fault conditions, what type of loads needs to be considered and utility specific distribution protection guidelines. It may take time before the industry agrees on a common definition and understanding. This article is not intended to conclude whether effective grounding is valid for the inverter based DER or not. Instead, it explains the different effective grounding options available and lists several utility guidelines.

### *Effective Grounding using the inverter's internal transformer*

Many grid tied PV inverters have an internal transformer. If the transformer is wye-delta configured with the wye on the grid side, the neutral terminal can be used for effective grounding as shown in Figure 3 a). In most of the cases, the grid voltages are well balanced and the distribution loads contain limited harmonic current. In that case, the inverter operates normally.

If the distribution line voltages are not well balanced and/or feeder voltage includes high zero sequence harmonic content, the transformer neutral provides a path for zero sequence current and considerable current can flow into the PV inverter's transformer. If the grounding impedance is low (the worst case will be solid grounding), the zero sequence current can be severe even with small voltage imbalances as the transformer impedance is relatively small. This neutral current can flow in through all three phases and can create the following issues:

i) If the grounding impedance is small, the neutral current can be significant, resulting in additional transformer heat loss.

ii) The neutral current can deteriorate the phase current harmonic content. Although the neutral current is not generated by the inverter itself, the zero sequence harmonics content that is measureable in the output current may exceed IEEE1547 levels.

iii) If the grid includes high frequency harmonics these harmonic currents are also sunk into the transformer neutral, increasing the neutral RMS current further.

Although the inverter power electronics on the transformer's delta side are not affected, effective grounding using the inverter's internal transformer neutral connection influences the transformer operation and the output current waveform. Depending on the site's power quality and impedance, it is possible that a listed inverter can draw excessive zero sequence currents due to the neutral grounding, which can be mitigated by increasing the grounding impedance.

### *Effective Grounding using a grounding bank*

As was explained previously, a grounding bank provides the same effective grounding as the grounding reactor connected to the transformer neutral as shown in Figure 3 b). As the device is connected external to the inverters, it allows for the inverters to be connected without neutral. If there are multiple inverters used in a PV plant, only one grounding bank is required at the PCC to achieve effective grounding for the whole plant.

### *Utility guidelines*

Depending on the distribution feeder protection scheme, there are some utility companies that protect the distribution equipment and loads from overvoltage by using overvoltage relays and therefore do not require effective grounding.

Utilities in Northeastern part of the United States currently use the conventional effective grounding concept prescribed in IEEE 142. The standard says "*The grounding scheme of the DR interconnection shall not cause overvoltage that exceeds the rating of the equipment connected to the Area EPS and shall not disrupt the coordination of the ground fault protection on the Area EPS.*" The grounding impedance ($X_0$) is calculated based on the positive sequence impedance ($X_1$) provided by the inverter manufacturer and $X_0/X_1 = 3$ is generally used. In some limited cases, the utility companies allow solid grounding if the inverters are proven to trip out fast during the distribution line faults.

Some utility companies acknowledge that the inverter based DERs are different from conventional generators and uses the following equation to calculate the zero sequence inductance. This equation does not use $X_1$, so that it eliminates the uncertainty of how the positive sequence impedance is to be defined.

$$X_{0,DG} = 0.6 \pm 10\% \; p.u. \tag{2}$$

Sequence network analysis and intensive PV inverter computer model simulation show that the worst case overvoltage can be limited to about 130% of its nominal value by following this criterion.

As a comparison of two different approaches of utility grounding impedance guidelines, a 500kW PV inverter connected to a 480VAC distribution feeder is studied; The required zig-zag grounding transformer impedance to meet the conventional effective grounding guideline according to equation (1) is 0.52 ohms, whereas the grounding transformer impedance which satisfies equation (2) is only 0.13 ohms. The smaller impedance provides an advantage in that the possible overvoltage with a single-line-to-ground fault will be lower. The disadvantage is the fault current absorption of the PV plant will be relatively higher so that it may influence the distribution feeder overcurrent protection coordination.

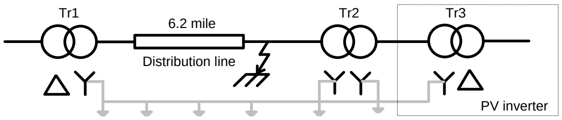
This large difference in the required impedance calculation originates from the different understanding of the inverter operation during a fault condition and the different protection strategies that utility companies are following to protect the distribution feeder. It is not clear as to when an industry standard will be published on a universally consented grounding impedance design guideline for inverter based DERs. Until then, PV plant developers should understand the local utility guidelines and provide grounding accordingly.

## V. PRACTICAL CONSIDERATIONS WITH EFFECTIVE GROUNDING

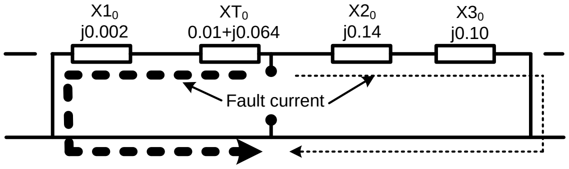
In this section, several different practical DER configurations are introduced to further illustrate the previous discussion. The distribution line and transformer impedances used in these examples are typical distribution feeder parameters in p.u. with a base of 1MVA and a 500kW PV inverter model is used as a distributed generator.

Figure 6 (a) shows a simplified diagram of a single-line-to-ground fault applied to a PV plant with a dedicated YG-YG transformer (Tr2) in a distribution feeder. The PV inverter can be a single inverter or an aggregation of multiple small PV inverters. Tr3 represents an internal transformer of a PV inverter. The neutral of the wye-delta transformer is used to provide solid grounding so that this configuration meets the conventional effective grounding requirement at the PV inverter level.

The investigation of the zero sequence impedance network as shown in Figure 6 (b) reveals that the majority (78%) of the fault current will flow into the higher voltage network as its associated impedances ($X1_0$ and $XT_0$) are lower than those of the PV plant circuits ($X2_0$ and $X3_0$).



*a) A Simplified DER Configuration in a Distribution Feeder*



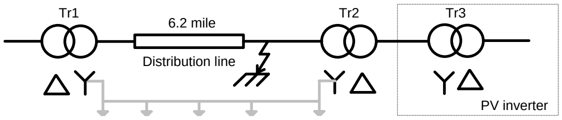
*b) Zero Sequence Equivalent Circuit during a Fault Condition*

Figure 6. Four-Wire Multi-Grounded System with a Dedicated Medium Voltage Transformer (YG-YG) for a PV plant

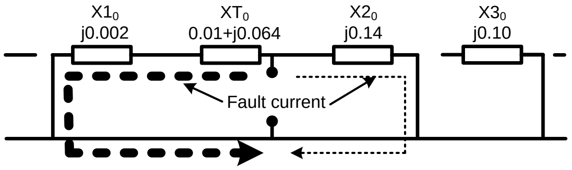
Nevertheless, about 22% of the fault current flows into the PV plant through the grounded network. If the PV plant were not introduced, 100% fault current flows to the high voltage network and trigger the upstream overcurrent protection relay. 22% reduction in the fault current can desensitize the distribution feeder protection coordination.

In order to mitigate this issue, utilities usually request to apply a zero sequence reactance. In this case, a grounding reactor will be installed at the inverter neutral similar to the diagram shown in Figure 3 a). If $X_0 / X_1 = 3$ is used for effective grounding, the fault current contribution from the utility side can be brought back up to more than 90% of the total fault current, so that the desensitizing is no longer an issue.

Figure 7 shows a similar configuration with the effective grounding accomplished at the medium voltage step-up transformer. As the low voltage side of the medium voltage transformer is configured in delta, the PV inverter is connected to a three wire system and PV inverter does not need to provide effective grounding.



*a) A Simplified DER Configuration in a Distribution Feeder*

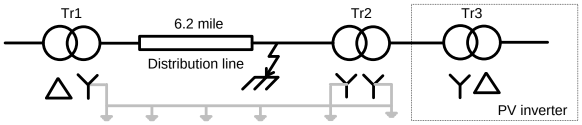


*b) Zero Sequence Equivalent Circuit during a Fault Condition*

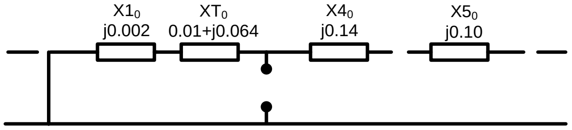
Figure 7. Four-Wire Multi-Grounded System with a Dedicated Medium Voltage Transformer (YG-Delta) for a PV plant

This is most desirable and most economical configuration especially when there are multiple inverters installed in the plant. The medium voltage transformer is outside of the PV inverter and effective grounding is achieved at the medium voltage level by means of a grounding reactor or a grounding bank.

Figure 8 shows a case of a single-line-to-ground fault applied to a system with YG to YG transformers connected to a PV inverter without the neutral grounding.



*a) A Simplified DER Configuration in a Distribution Feeder*



*b) Zero Sequence Equivalent circuit during a Fault condition.*

Figure 8. A PV plant not complying an effective grounding

A PV plant is connected to the distribution feeder with a dedicated medium voltage transformer (Tr2). The neutral of Tr2 is connected to the neutral of substation transformer (Tr1) using three phase four wire system so that it seems like the plant is effectively grounded. However, as shown in Figure 8 (b), the medium voltage transformer and the PV inverter are isolated in the zero sequence equivalent circuit. Therefore, when the feeder is isolated and a single-line-to-ground fault is applied to this feeder, an overvoltage can be generated on the unfaulted phases and customer loads can be damaged. This is one particular case that can be easily overlooked by engineers who deal with effective grounding. As long as the wye-delta transformer (Tr3) is not grounded or a separate grounding transformer is not used, effective grounding cannot be accomplished by using a YG to YG transformer alone.

## VI. SUMMARY

Effective grounding is relatively a new concept in the PV industry and there are several ways to achieve it. If a project is planned properly according to the local utility requirements, there are ways to economically and adequately provide effective grounding. The following guidelines can be used to consider possible effective grounding options from the initial stage of project planning:

- Whenever possible, adopt a plant level effective grounding scheme by using a wye–delta medium voltage transformer or using a grounding bank rather than providing individual effective grounding at the inverter level.

- In order not to desensitize the protective relay settings, use the highest possible grounding impedance that still meets the effective grounding criteria specified by the utility.

- A grounding bank is a preferred option to meet the effective grounding requirement for sites with multiple inverters. If internal transformer neutral has to be used, there is a potential issue of power quality and plant efficiency reduction.

- A grounding reactor or grounding bank is usually rated for short term duty. If they are not rated for continuous duty, an overcurrent protection needs to be used to prevent overheating during a fault condition.

- The neutral point of the Solectria inverter's internal transformer can be used for effective grounding. The products are designed to handle the higher short circuit currents and additional heat from harmonic currents that can result when a neutral wire connection to the inverter is made. Inverter user manuals include information on the landing terminal and the wire gauge that can be used.

## References

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