Effective Grounding on Inverter-Connected DER

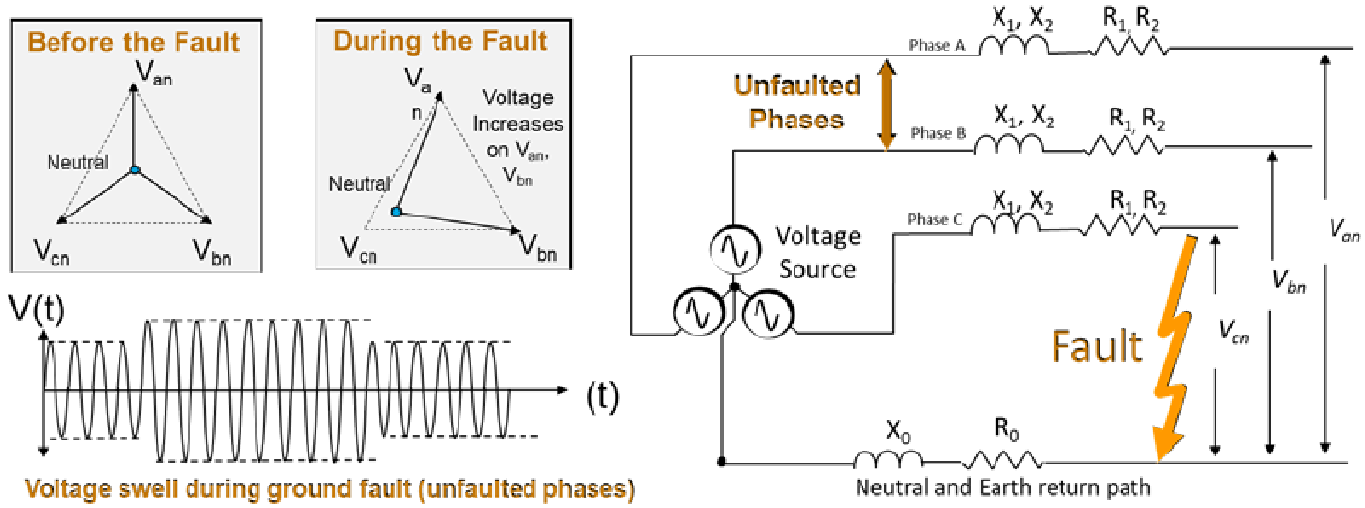

Fig. 1, Overvoltage caused by neutral shift during ground fault

Source: 'Effective Grounding for Inverter-Connected DER:Final Report', Figure 1-1, Electric Power Research Institute[1]

IEEE Std C62.92.6-2017 provides guidance on the Application of Neutral Grounding in Electrical Utility Systems Supplied by Current-Regulated Sources such as Solar PV Systems or other Inverters[2]. In addition, EPRI has expanded on the following:

- Effective Grounding for Inverter-Connected DER: Final Report[1], and
- Effective Grounding and Inverter-Based Generation: A "New" Look at an "Old" Subject[3].

This Application Guide provides Mirus' interpretation of the Standard and the EPRI publications and further guidance to assist in the implementation of their recommendations.

Please note that Mirus is not responsible for any misinterpretation of the standard, the report or their guidance. The following notes are Mirus' interpretation only.

An Inverter based Distributed Energy Resource (DER) is expected to have an insignificant effect on the system grounding when in normal parallel operation with the Utility. However, when in unintentional islanded mode with the feeder breaker open, ground fault overvoltages (GFOV) may occur due to disconnection of the system neutral ground and the resulting neutral point shift (Fig. 1). This should be averted to prevent equipment failure even if it is only for a very short duration due to anti-islanding controls.

To this end, the concept of Effective Grounding is applied. Coefficient of Grounding (CoG), as defined in IEEE C62.92.1-2016[4], is used to determine Effective Grounding.

$$CoG = \frac{V_{L-G(fault)}}{V_{L-L(no\ fault)}}$$

A system is effectively grounded when grounded through a sufficiently low impedance such that the CoG does not exceed 80% (≤ 0.8 pu). This limits the GFOV to:

$$GFOV_{limit} = 0.8 \times V_{L-L} = 0.8 \times \sqrt{3} \times V_{L-G} \approx 138\%\ of\ V_{L-G}$$

For synchronous generators, which have relatively low zero sequence impedance, ratios of $X_0/X_1 \leq 3$ and $R_0/X_1 \leq 1$ have been determined to establish effective grounding where:

X_0 = DER system zero sequence reactance
X_1 = DER system positive sequence reactance
R_0 = DER system zero sequence resistance

Depending on the interconnecting transformer configuration, supplemental grounding in the form of a parallel connected grounded zigzag or Yg-Delta transformer may be necessary.

But for current regulated inverters with near infinite source impedances, both positive sequence and zero sequence, these ratios are no longer suitable for determining effective grounding. This is true even if the current source inverter has a grounded neutral connection because the connection normally provides only a neutral reference and not a ground fault path.

Connected load impedances, which are negligible in synchronous generator applications, are critical in systems driven by current sources. If the majority of the load is phase-to-ground connected and the power output of the source is not significantly greater than the demand load, supplemental ground sources are not required to ensure effective grounding. See Fig. 2 where overvoltage is < 1.38x the L-N voltage when the grounded load is > 33%. So if more than 33% of the connected loads are grounded L-N, C62.92.6 states that supplemental grounding is not recommended.

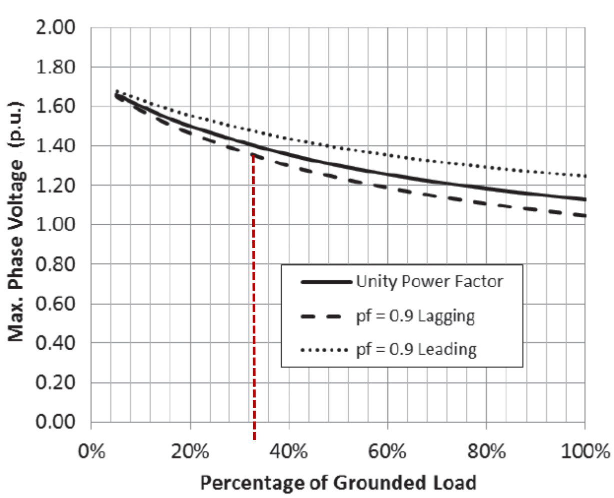

Fig. 2, Maximum unfaulted phase voltage vs % load connected phase-ground
Source: IEEE Std C62.92.6-2017, Fig. B.2[2]

When a service is 120/208V or 220/415V, it is quite likely that the L-N loads will be greater than 33%. On services of higher voltage and for 3-wire services, there will be few if any L-N loads so supplemental grounding will likely be required to limit GFOV. The design parameters for this ground source however, are different than for synchronous generators.

This is due to the fact that, for a current regulated inverter application, the load, rather than source, defines the system impedance at the fault point. These loads are more substantially resistive so a grounding source that is more resistive than inductive is more effective. So when the load configuration requires supplemental grounding, C62.92.6 recommends that this grounding be more resistive than inductive.

Although C62.92.6 doesn't specifically define design parameters for the supplemental grounding, EPRI provides recommendations based on symmetrical component analysis. The following graph shows the relative resistance and inductance values of the ground source needed to meet the effective grounding requirement of CoG < 0.8.

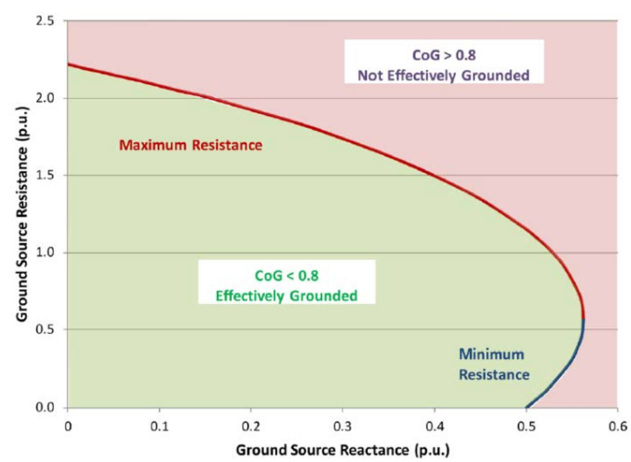

Fig. 3, Ground source zero sequence resistance and reactance to provide effective grounding
Source: 'Effective Grounding and Inverter-Based Generation: A "New" Look at an "Old" Subject', Fig. 4, EPRI[3]

This has been further simplified to $0.01 \le X_0/R_0 \le 0.3$ and $1 \le Z_0/Z_{1load} \le 2$ where:

X_0 = DER system zero sequence reactance
R_0 = DER system zero sequence resistance
Z_0 = DER system zero sequence impedance
Z_{1load} = load positive sequence impedance

When supplemental grounding is applied, C62.92.6 describes adverse impacts that can occur as follows:

I. Utility ground fault protection could be desensitized due to fault current splitting between Utility fault path and supplemental ground fault path.

II. Single phasing may not be detected and interrupted.

III. Increased ground fault current magnitudes.

A 4th condition that should also be considered is that the low zero sequence impedance of supplemental grounding can provide a path for the continuous flow of common-mode circulating current. This can result from voltage imbalance or common-mode harmonic voltages which makes it difficult to predict. So if supplemental grounding can be averted it is preferred. But when it is necessary, these four conditions should be taken into consideration.

When it is determined that supplemental grounding is required, Mirus recommends the following:

I. NCE-FAI: A zigzag grounding transformer designed to the loading requirements of IEEE Std 32 – 'Standard Requirements, Terminology, and Test Procedure for Neutral Grounding Devices'[5] with taps for adjustment of zero sequence reactance, X_0.

II. DPNL: A neutral blocking reactor designed to provide high impedance to neutral circulating current but low impedance to fault current.

This allows the requirements of IEEE C62.92.6 to be addressed without introducing high levels of common-mode circulating current that could overload the grounding devices.

Application Example:

A 700 kW Solar Plant in Saskatchewan Canada was installed with a zigzag grounding transformer and neutral grounding resistor to protect against GFOV during even brief islanding operation as described in IEEE C62.92.6. The phase-to-ground connected load was determined to be < 33%, requiring supplemental grounding to limit GFOV. The connected load impedance was calculated to be 0.5864 ohms meaning a Z_0/Z_{1load} ratio of 1 required a supplemental grounding system of Z_0 = 0.5864 ohms. Also, the design was to have $X_0/R_0 \leq 0.3$.

To meet these design parameters, the supplemental grounding system included a zigzag grounding transformer, with X_0 = 0.1685 ohms and R_0 = 0.0421 ohms (X_0/R_0 = 4), plus neutral grounding resistor (NGR) of 0.173 ohms. This resulted in an X_0/R_0 ratio for the combined system of (0.1685/(0.0421 + 3*0.173) = 0.299.

Although this ground system seemed to meet the IEEE C62.92.6 requirements, the protection system immediately tripped when energized due to a measured circulating neutral current of 147A which exceeded the ratings of both the grounding transfomer and the NGR.

Mirus was asked to provide a supplemental grounding system design that would meet the requirements while blocking the circulating current. To block the circulating current, a GenLink DPNL[6] zero sequence blocking reactor was proposed (https://www.mirusinternational.com/genlink.php). This reactor inserts high impedance (X_0~15 pu) to the common-mode circulating current but low impedance (X_0 ~ 2 pu) in the fault current path when saturated during the fault. The blocking impedance was expected to reduce the circulating current by more than 75%.

The design proposed by Mirus to meet the minimum required Z_0 of 0.5864 ohms at this site included a wire wound neutral resistor as follows:

1. NCE-FAI, 175A
   - X_{0NCE} = 0.0237 ohms
   - R_{0NCE} = 0.0479 ohms
   - Z_{0NCE} = 0.0534 ohms
2. DPNL, 200A
   - X_{DPNL} = 0.0662 (sat) = 0.3995 (unsat) ohms
     X_{0DPNL} = 0.1986 (sat) ohms
   - R_{DPNL} = 0.01 ohms, R_{0DPNL} = 0.03 ohms
   - Z_{0DPNL} = 0.067 ohms (sat)
3. Neutral Resistor,
   - R_{NR} = 0.22 ohms, R_{0NR} = 0.66 ohms

The total zero sequence impedance values of this supplemental grounding system meet the IEEE C62.92.6 requirements with an X_0 to R_0 ratio of 0.3 and a Z_0 = 0.77 resulting in a Z_0 to Z_{1load} ratio of 1.31.

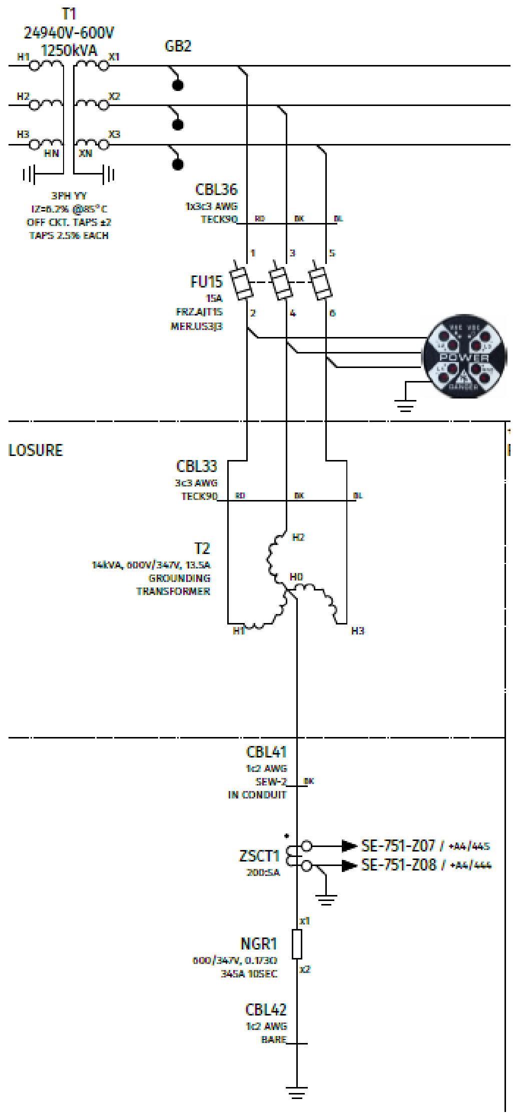

Fig. 4, Original supplemental grounding system that experienced high circulating current

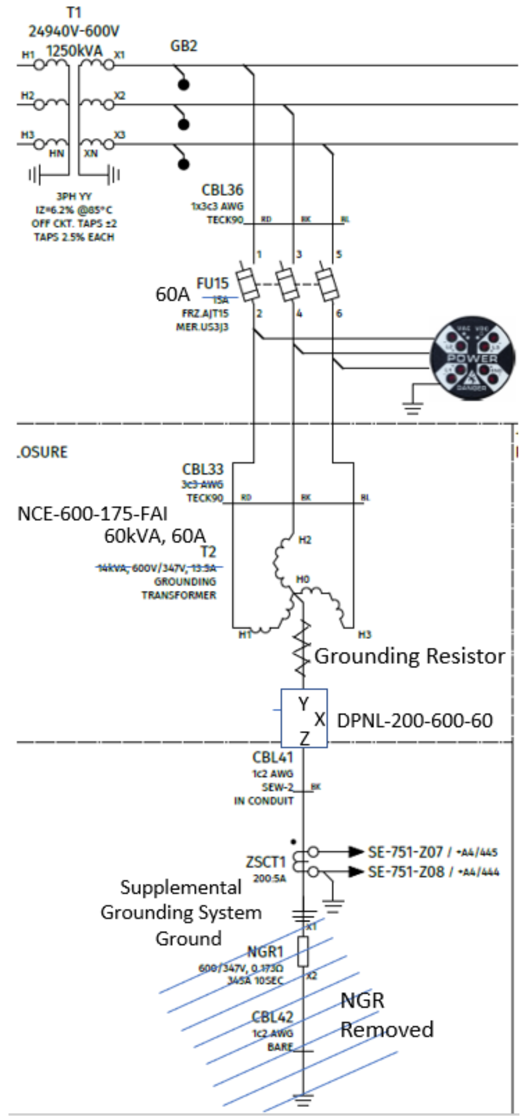

Fig. 5, Mirus proposed supplemental grounding system that limits circulating current

As the implementation of Solar Power Distributed Energy Systems utilizing current regulated inverters continues to grow, consideration for ground fault overvoltages has become more critical. But as a high impedance current source, the effective grounding requirements are different than for synchronous generator applications. IEEE Std C62.92.6 addresses this difference and defines requirements for supplemental grounding when the grounded connected load is < 33% of DER system capacity.

A solution combining a grounding transformer, grounding resistor and neutral blocking reactor will meet these defined requirements while also preventing common mode circulating current from overloading the grounding package.

References:

1. Effective Grounding for Inverter-Connected DER:Final Report', Electric Power Research Institute
2. IEEE Std C62.92.6-2017, Application of Neutral Grounding in Electrical Utility Systems, Part VI – Systems Supplied by Current-Regulated Sources
3. Effective Grounding and Inveter-Based Generation: A "New" Look at an "Old" Subject, Electric Power Research Institute
4. IEEE Std C62.92.1-2016, Application of Neutral Grounding in Electrical Utility Systems, Part I – Introduction
5. IEEE Std 32-1972, Standard Requirements, Terminology, and Test Procedure for Neutral Grounding Devices
6. DPNL-TG001-A, GenLink DPNL Technical Guide, Mirus International Inc