Addressing Zero Sequence Continuity for DER Connections with High Impedance Grounded Utility Interconnection Transformers

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Abstract— **With increasing distributed energy resource (DER) penetration, utilities and DER owners are encountering technical challenges in relation to PCC measurement. This challenge is exacerbated when the interconnection transformer breaks zero sequence continuity but is owned by the utility and not the DER owner. This industry paper presents a reliable solution for both DER owners and electrical utilities for DER connections where the interconnection transformer is grounded through a high impedance. The solution can be implemented by DER owners without the need to shift the reference point of applicability for the DER to maintain zero sequence continuity. The proposed solution is tested in EMTP-RV to verify efficacy of the method.**

Index Terms—**Zero-sequence continuity, DERs, distribution.**

I. Introduction

As a result of societal objectives and desires globally, the adoption of renewable energy resources within electrical networks is becoming increasingly prevalent within the energy mix. Conducive markets are resulting in increased presence of distributed energy resources (DERs) in distribution networks. With the increase of DERs in the generation mix, utilities are relying on interconnection standards to ensure safe and reliable connections that do not compromise grid stability [1].

A key component with the application of standards such as IEEE 1547-2018 [1] lies in the designation of the reference point of applicability (RPA). The RPA is the location where the performance requirements for DER connections shall be met. The two main factors that determine RPA location are DER aggregate nameplate rating and the existence of zero sequence continuity (note there is a third criteria related to load demand, but it is not a common connection type) [1]. If zero sequence continuity is broken or the DER is greater than 500 kW, the RPA is usually at the point of common coupling (PCC) [2].

Zero-sequence continuity refers to the property in a three-phase power system whereby the zero-sequence components—currents or voltages that are equal in magnitude and in phase across all three phases—maintain a continuous conductive path through a network element or connection. The concept arises from symmetrical component analysis, in which the system is represented by positive-, negative-, and zero-sequence networks [3]. Zero-sequence continuity exists when a low-impedance conductive path allows zero-sequence current to flow between two system points—such as across a wye–wye transformer with both neutrals grounded, or through a solidly grounded neutral in a four-wire feeder [2]-[3]. A break in zero sequence continuity occurs when the zero-sequence path is blocked or opened resulting in no ability for zero sequence currents to flow [2]-[3]. Traditionally, it is well understood that a break in zero sequence continuity occurs for interconnection transformers involving a delta winding which confines the zero sequence currents to circulate within the delta winding [4]. In high-impedance grounded or resistance-grounded systems, zero-sequence continuity formally exists, but the high neutral impedance restricts the magnitude of zero-sequence current. Under these conditions, zero-sequence voltage continuity is maintained, but current continuity is effectively attenuated, and the network behaves as partially continuous. IEEE Std. 142-2007 [5] and IEC 60909 [6] treat such cases as zero-sequence circuits with finite but large impedance. Operationally, maintaining zero-sequence continuity is critical in systems employing distributed energy resources (DERs). Breaks—or very high impedances—in the zero-sequence path alter effective grounding, modify zero-sequence impedance seen by faults, and can cause neutral voltage shifts, elevated line-to-ground voltages, or protection mis-operations during distribution network events [1]-[2]. This is a particularly challenging issue when the distribution system operator (DSO) owns the interconnection transformer.

The authors have confirmed that there are little to no established practices for DSOs to address protection related issues with DER connections when the DSO owns the transformer breaking the zero-sequence continuity. As such, there is a gap in literature that is required to be mended. This industry paper presents a proposed definition for quantifying a break in zero-sequence continuity in addition to providing a solution for PCC measurements for DERs connected through a high impedance grounded interconnection transformer owned by the DSO. Solution efficacy is verified in EMTP-RV.

II. Proposed Definition for a Break in Zero-Sequence Continuity

A. Proposed Definition

As mentioned, a break in zero-sequence continuity is problematic for DER connections as the voltages at the point of DER connection (PoC) may not be representative of the voltages at the PCC under abnormal voltage conditions [2].

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This can result in difficulties in 'sensing' ground faults or failure to detect ground fault overvoltages. Additionally, the DER can fail to detect abnormal voltage conditions when a DER feeds onto the distribution network during open-phase conditions [2]. To address this, typically, DERs are required to perform sensing for protection at the PCC where zero-sequence continuity is broken. Generally, it is well understood that delta windings break zero-sequence continuity where the differences between the zero-sequence voltage on the high voltage side and low voltage side is significant. This becomes more complicated with high impedance grounded transformers as under these conditions, zero-sequence voltage continuity is maintained, but current continuity is effectively attenuated, and the network behaves as partially continuous. There is no formal definition or threshold for defining when zero-sequence continuity is broken in the context of DERs. As a result, the 2 following equations are being considered for a break in zero sequence continuity between two points:

$$\Delta V_0 = |V_{0A} - V_{0B}| \quad (1)$$

$$\delta_{V_0} = \frac{|V_{0A} - V_{0B}|}{|V_{0A}|} \quad (2)$$

Where Equation (1) (ΔV_0) is the absolute change in zero sequence voltage between points A and B, $V_{0A/B}$ is the zero sequence voltage of points A and B during a distribution system disturbance. Equation (2) (δ_{V0}) is the normalized change in zero sequence voltage based on the local zero-sequence voltage magnitude. The normalized form yields a dimensionless index that scales the discontinuity relative to the reference value (A).

The issue with Equation (2) is that it can exaggerate the apparent discontinuity when the zero-sequence voltage magnitude is very small (e.g. during inverter momentary cessation conditions or during deep undervoltage conditions). For example, if V_{0A} is 0.01 per unit and V_{0B} is 0.02 per unit then (2) will produce a 100% difference even though both voltages are near zero and the DER would trip or be in a ceased state. In the cases of small voltages, the normalized deviation would not correspond to a meaningful break in zero-sequence continuity from a protection context. To ensure robustness of the physical interpretability (2) is instead expressed being normalized by the nominal system base voltage rather than a voltage at a specific location. This approach aligns with voltage-deviation and flicker assessment practices in IEEE 1547-2018 [1], ensuring that the continuity metric remains bound and comparable across all operating conditions. The resulting equation is expressed as:

$$\delta_{V_0} = \frac{|V_{0A} - V_{0B}|}{|V_{nom}|} \quad (3)$$

IEEE 1547-2018 states "individual DER units that are considered fully compliant at the PoC may only be considered fully compliant at the PCC if the impedance between the PoC and the PCC is less than 0.5% on the DER rated apparent power and voltage base". This can be extended to voltage as the difference in impedance can be directly translated to voltage deviations between locations using simple power equations. As such the authors propose using the same threshold as defined by IEEE 1547-2018 where a break in zero sequence continuity in the context of DER connections is defined by:

$$\delta_{V_0} < 0.5\% \quad (4)$$

The initial intent behind the 0.5% impedance rule in IEEE 1547-2018 was to ensure that voltage and frequency sensing at the DER point of connection (PoC) remain representative of the system voltage at the point of common coupling (PCC). The same principle is applied here for zero-sequence voltage continuity. When the zero-sequence voltage difference between two points exceeds 0.5 % of nominal, it indicates that the two locations are no longer electrically equivalent in the zero-sequence network.

However, it is important to recognize that some finite voltage difference is expected across any element that has non-zero zero-sequence impedance. For example, a grounded-wye–grounded-wye transformer with a typical 5% impedance maintains full zero-sequence continuity but will exhibit a measurable zero-sequence voltage drop under unbalanced or faulted conditions due to the zero-sequence voltage equaling the zero-sequence current multiplied by the zero-sequence impedance. This legitimate voltage drop should not be interpreted as a break in continuity. To account for this, a residual continuity metric can be introduced to remove the portion of the measured voltage difference that is physically explained by normal current flow through the transformer impedance. The residual is defined by:

$$\Delta V_{0,res} \approx |V_{0A} - V_{0B}| - |I_0||Z_{0,path}| \quad (5)$$

Where $Z_{0,path}$ is the Thevenin zero-sequence impedance between locations A and B. The relation in (5) is expressed as an approximation because it compares magnitude quantities rather than full phasors; the true phasor difference may not be colinear with $I_0Z_{0,path}$ due to phase-angle differences in the zero-sequence network, but the magnitude-based form provides a practical scalar metric for continuity assessment. When the path is continuous (e.g., for Yg–Yg transformers), the measured voltage step ΔV_0 is largely explained by the $I_0Z_{0,path}$ yielding a small residual. Conversely, when the path is open or blocked (e.g., for delta-connected windings), I_0 tends towards 0 and the full measured difference appears as residual, which exceeds 0.5%. In this way, the residual distinguishes true breaks in zero-sequence continuity from normal voltage drops that occur across grounded transformer impedances. Here the $I_0Z_{0,path}$ is the sequence zero-sequence impedance between A and B; the neutral element's $3Z_n$ contribution is already embedded, so the expected drop term is $I_0Z_{0,path}$ (not $3I_0Z_{0,path}$). As a result, criterion (4) becomes:

$$|\Delta V_{0,res}| < 0.5\% \quad (6)$$

All quantities in (1) - (6) are expressed in per-unit on a common 100 MVA, nominal line-to-neutral voltage base; therefore, explicit normalization by V_{nom} is redundant in (5) and (6). The product $I_0Z_{0,path}$ already yields a per-unit voltage since both current and impedance are expressed in per-unit on the same base.

B. Proposed Definition Discussion

As mentioned, the proposed zero-sequence continuity expression builds upon established sequence network modelling principles used in references [5]-[6]. In both contexts, open and blocked zero-sequence paths are represented as open circuits in a zero-sequence network yielding a zero-sequence current of zero and zero-sequence impedance tending to infinite. Because a delta winding provides no conductive path

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for zero-sequence current, the zero-sequence networks on each side are completely isolated. Under unbalanced or ground-faulted conditions, each side establishes its own zero-sequence potential with respect to ground. Even small neutral shifts or imbalances, on the order of a few volts line-to-ground, translate to several percent of the nominal line-to-line voltage. As a result, the normalized zero-sequence voltage deviation expressed in (3) and (4) consistently exceeds 0.005 per unit in practice, typically ranging from a few percent to several percent. Thus, any delta-connected interface inherently satisfies the criterion for a break in zero-sequence continuity criterion.

Conversely, solidly grounded or wye–wye configurations provide a low-impedance return path, ensuring continuity of both zero-sequence voltage and current. High-impedance-grounded systems occupy an intermediate state in which voltage continuity is largely maintained, but current flow is substantially attenuated, producing the "partially continuous" condition modeled by (3).

IEEE Std 1547-2018 does not explicitly define zero-sequence continuity; however, it implicitly constrains its effects through the 0.5 % impedance limit between a DER's point of connection (PoC) and the point of common coupling (PCC). That clause ensures that voltage deviations between these two locations remain negligible such that compliance verified at the PoC remains valid at the PCC. The present formulation extends this principle to the zero-sequence domain, where (3) and (4) serve as an analogous limit for assessing if the zero-sequence network is essentially continuous. From a utility-protection perspective, adopting a quantitative zero-sequence continuity threshold enhances the consistency of DER interconnection assessments.

III. Proposed High Impedance DER Connection

A. RPA Definition Problems

As mentioned previously, DER demarcation points and RPA determination are relatively simple. An issue presents itself for RPA determination and system impacts when the demarcation between DSO and DER assets in conjunction with zero-sequence continuity requirements A break in zero-sequence continuity is problematic for DER connections as the RPA is typically required to be upstream of the DER owned assets. Such a case is where the DSO owns the interconnection transformer breaking zero-sequence continuity and the DER is located downstream of the connection. In these cases, DSOs may require the sale of the interconnection transformer to ensure that the DER can purchase high voltage protection equipment to be placed on the high voltage side of the interconnection transformer. Another solution is forcing multiple demarcation points where the DER owners own switchgear on the high voltage side of the DSO owned interconnection transformer. In either case operational complexities exist.

B. The Sample system.

Fig. 1 represents an actual system configuration that is currently requesting connection of a DER downstream of a DSO interconnection transformer that has a high impedance grounded connection. Note, unless otherwise specified all per unit calculations are on a 100 MVA and 25 kV base. The load service is connected through an interconnection transformer with a Yg high voltage winding with a Yg low voltage winding grounded through a 96-ohm neutral ground resistor (NGR). The NGR inclusion is due to customer operational requirements and was unable to be removed to permit a wye-ground to wye-ground connection. The load is approx. 1.1 MW with a 3% imbalance. The transformer is owned by the DSO and the DER applying to connect is 800 kW solar. According to IEEE 1547-2018 [1], the RPA is the PCC which is technically the low voltage bushing of the DSO owned interconnection transformer. The issue is with the presence of the 96-ohm NGR, the zero sequence continuity between the DSO and the customer could be broken. Applying a bolted single line-to-ground fault at the DSO substation yields the results in Fig. 2.

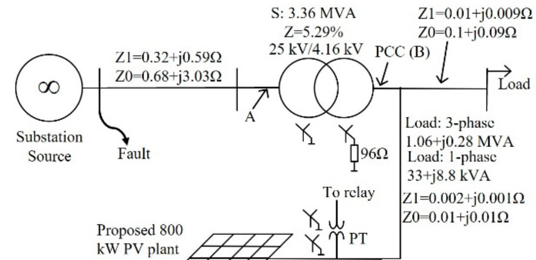

Fig. 1. Sample System SLD.

The load service is connected through an interconnection transformer with a Yg high voltage winding with a Yg low voltage winding grounded through a 96-ohm neutral ground resistor (NGR). The NGR inclusion is due to customer operational requirements and was unable to be removed to permit a wye-ground to wye-ground connection. The load is approx. 1.1 MW with a 3% imbalance. The transformer is owned by the DSO and the DER applying to connect is 800 kW solar. According to IEEE 1547-2018 [1], the RPA is the PCC which is technically the low voltage bushing of the DSO owned interconnection transformer. The issue is with the presence of the 96-ohm NGR, the zero sequence continuity between the DSO and the customer could be broken. Applying a bolted single line-to-ground fault at the DSO substation yields the following voltage results:

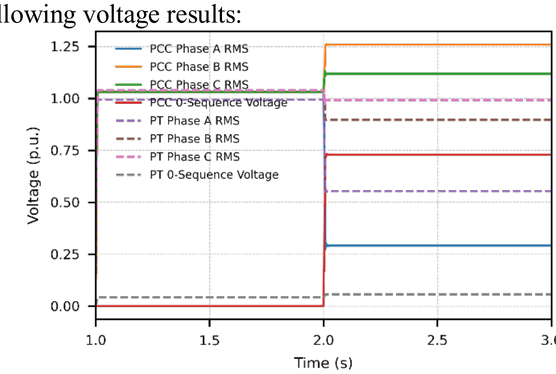

Fig. 2. Voltage measurements for a fault applied at the DSO substation for the sample case.

As can be seen in Fig. 2, the high voltage PCC zero sequence voltage measured is 0.728 per unit while the low voltage potential transformer (PT) measures 0.056 per unit. The zero-sequence current is 0.931 A (0.0004 per unit) while the equivalent zero-sequence impedance for the path is (1.57+46.08) 47.65 per unit. Using (5) yields:

$$|\Delta V_{0,res}| = |0.728 - 0.056| - |0.0004||47.65| = 65.3\% > 0.5\% \quad (7)$$

As such zero-sequence continuity is considered broken for protection purposes.

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For completeness, assume that the low voltage transformer winding is solidly grounded (rather than through the 96-ohm NGR). Applying the bolted single line-to-ground fault at the DSO substation yields the results in Fig. 3.

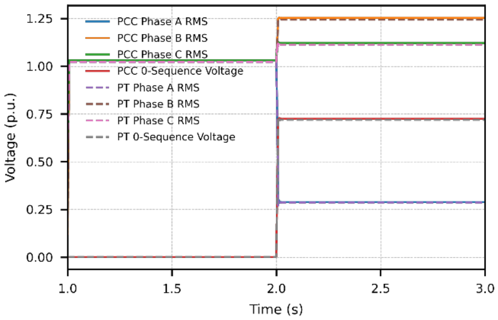

Fig. 3. Voltage measurements for a fault applied at the DSO substation for the modified sample case where the low voltage winding is solidly grounded.

As can be seen in Fig. 3, the high voltage PCC zero sequence voltage measured is 0.728 per unit while the low voltage potential transformer (PT) measures 0.719 per unit. The zero-sequence current is 18.2 A (0.0079 per unit) while the equivalent zero-sequence impedance for the path is 1.57 per unit. Using (5) yields:

$$|\Delta V_{0,res}| = |0.728 - 0.719| - |0.0079||1.57| = 0.34\% < 0.5\% \quad (8)$$

As such zero-sequence continuity is not considered broken. As such the removal of the NGR would re-establish zero-sequence continuity. The issue, in this case, is that the NGR is critical for customer operations and cannot be removed.

To further test the break-in-zero-sequence-continuity criterion, the low-voltage transformer winding was modified from grounded-wye (with a 96 Ω NGR) to delta. A bolted single-line-to-ground fault was again applied at the DSO substation, and the resulting voltage measurements are shown in Fig. 4.

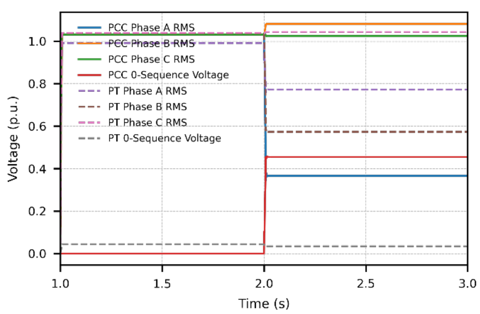

Fig. 4. Voltage measurements for a fault applied at the DSO substation for the modified sample case where the low voltage winding is delta.

As shown in Fig. 4, the high-voltage PCC zero-sequence voltage is 0.455 per unit, while the low-voltage PT measures 0.034 per unit. Because a delta winding blocks zero-sequence current transfer, the zero-sequence circuit between the two windings is effectively open, such that I_0 tends to 0 and $Z_{0,path}$ becomes very large. In practice, both quantities remain finite as the delta provides a high-impedance capacitive and resistive return path to ground so the product $I_0Z_{0,path}$ yields a finite voltage consistent with the observed potential difference, rather than a true mathematical indeterminacy. Substituting into (5):

$$|\Delta V_{0,res}| = |0.455 - 0.034| - |I_0||Z_{0,path}| \approx 42.1\% > 0.5\% \quad (9)$$

This clearly indicates a break in zero-sequence continuity. Physically, the grounded-wye side responds to unbalanced or faulted conditions, while the delta side remains largely isolated in the zero-sequence network, maintaining its own potential through high-impedance leakage and parasitic coupling. Because the continuity metric in (5) removes the portion attributable to normal current-coupled voltage drops, the residual captures the remaining uncorrelated potential difference. Thus, even with the finite high-impedance path inherent to a delta winding, the residual remains several orders of magnitude above the 0.5 % threshold, confirming a complete break in zero-sequence continuity and validating the criterion.

To further test the criterion in (5), a 70 km feeder was analyzed using system short-circuit data representative of a rural 25 kV network in an actual utility network. The system impedances at the PCC are Z_1=3.57+j5.15% and Z_0=4.54+j17.18%, corresponding to a three-phase short-circuit capacity of approximately 16 MVA on a 100 MVA base. For a bolted single line-to-ground (SLG) fault at the PCC, the resulting zero-sequence current magnitude is I_0≈26A. A 10 MVA, 7 % impedance Yg–Yg transformer was applied at the DER interface, giving $Z_{0,path}$=0.7 per unit. The expected voltage deviation across the transformer is $I_0Z_{0,path}$=0.0078 per unit, while the measured voltage difference between the PCC and DER low voltage PT is approx. 0.008 per unit. This gives a $|\Delta V_{0,res}|$=0.0002 per unit (0.02%) which is well below the threshold of 0.5%. This confirms that even along a long feeder, a continuous zero-sequence path through a solidly grounded transformer maintains a consistent voltage profile between the PCC and PoC.

IV. Proposed Solution for the Connection

A. Proposed Solution Explanation

To address the zero-sequence continuity issue presented in Fig. 1's system, the authors have proposed extending the neutral from the star point of the low voltage wye winding to the new solar switchgear assembly where PTs will perform the protection and control measurements. By doing this, the PTs will then be able to provide line-to-neutral and line-to-line measurements representative of the per unit values on the high voltage side of the DSO interconnection transformer (where zero-sequence continuity was broken) in compliance with requirements for a 4-wire system in IEEE 1547-2018 [1]. The solution is depicted with an updated system SLD in Fig. 5.

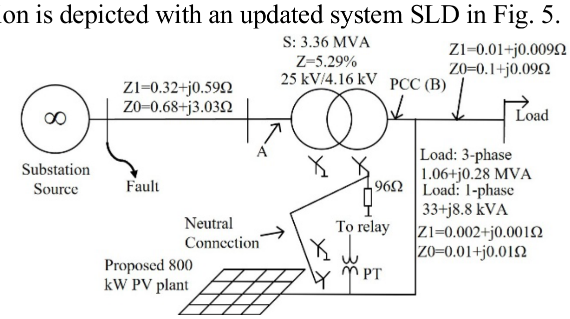

Fig. 5. Sample System SLD with the proposed solution.

While it is customary for load users to treat a high impedance grounded system as an ungrounded 3-wire system, the presence of a neutral technically makes the system a 4-wire grounded system for which IEEE 1547-2018 does not distinguish between impedance grounding, effective grounding and solid grounding. In short, by making the ground reference of the PT solid through the star point of the low voltage wye winding, it bypasses the NGR which would make the

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measurements as though the interconnection transformer was a wye-ground wye-ground connection. The neutral extension is for measurement only and does not defeat the NGR function.

B. Canadian Electrical Code Considerations

The Canadian Electrical Code (CEC), CSA C22.1-24 [7], governs grounding in Section 10 and Section 36 for systems above 750 V. "Grounded" denotes a low-impedance connection to earth capable of preventing harmful voltages under fault conditions. A high-resistance or impedance-grounded neutral behaves functionally ungrounded during severe faults. Rules 10-300 to 10-308 specify qualified maintenance, insulation rated to nominal line-to-line voltage, ground-monitoring and alarms, and requirements for conductor sizing, identification, insulation, and warning signage. High-resistance grounded systems cannot serve as four-wire wye sources [8]. Section 36-308 allows impedance grounding, but its Subrule 6 applies only to solidly grounded systems, confirming permissibility of impedance-grounded neutrals. Section 84 mandates conformance with the supply authority's interconnection requirements (Rules 84-002 to 84-014), including IEEE 1547-2018 compliance, whose Clause 4.3 requires measurement of phase-to-phase and phase-to-neutral voltages on three-phase, four-wire systems for undervoltage and overvoltage protection. Accordingly, phase-to-neutral potential transformers are required wherever a neutral exists, even on impedance-grounded systems, and the proposed configuration—retaining impedance grounding while adding phase-to-neutral voltage sensing—meets CEC Rules 10-300 through 10-308 and 36-308 and satisfies IEEE 1547-2018 and Section 84.

C. Proposed Solution Test

Similar to the tests run in the previous section, a bolted single line-to-ground fault at the DSO substation yields the voltage results in Fig. 6.

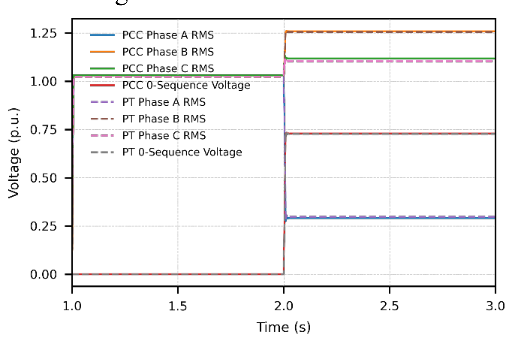

Fig. 6. Voltage measurements for a fault applied at the DSO substation for the sample case with the proposed solution.

As can be seen in Fig. 6, the high voltage PCC zero sequence voltage measured is 0.728 per unit while the low voltage potential transformer (PT) measures 0.727 per unit. The zero-sequence current is 0.931 A (0.0004 per unit) while the equivalent zero-sequence impedance for the path is 1.57 per unit. Using (5) yields:

$$|\Delta V_{0,res}| = |0.728 - 0.727| - |0.0004||1.57| = 0.04\% < 0.5\% \quad (10)$$

As such zero-sequence continuity is not considered broken and the site is now in full compliance with measurement requirements specified in IEEE 1547-2018.

VI. Discussion

The simulation results presented in this paper demonstrate that extending the neutral from the low-voltage wye winding to the DER switchgear restores zero-sequence voltage continuity, yielding $\delta_{V_0} = 0.001 < 0.005$ pu which is well within the proposed threshold. This confirms that the proposed configuration enables the DER protection relays to sense PCC-representative voltages without altering the existing impedance-grounded scheme. From a practical perspective, the modification is minimal, requiring only a neutral extension and appropriate impedance-grounded signage as prescribed by CEC Rule 10-306. Maintenance and protection integrity are preserved since the impedance grounding device, and monitoring system remain unchanged.

The approach is broadly applicable to medium-voltage DER interconnections where the DSO owns a high-impedance-grounded transformer, addressing a common regulatory and technical gap. However, applicability to systems with delta or ungrounded configurations remains limited, as these constitute complete zero-sequence isolation. Outside the scope of this paper, but planned for future works, is field verification of the proposed solution along with a testing plan.

VII. Conclusion

This paper introduced a quantitative definition for determining a break in zero-sequence continuity and applied it to high-impedance grounded DER interconnections. Using the proposed $\delta_{V_0} < 0.005$ threshold, derived from IEEE 1547-2018's impedance criterion, zero-sequence continuity can be objectively assessed using voltage measurements alone. EMTP-RV simulations verified that extending the neutral from the low-voltage winding to the DER switchgear re-establishes zero-sequence continuity while maintaining compliance with the Canadian Electrical Code and IEEE 1547-2018. The proposed approach allows DER owners to achieve PCC-representative measurements without ownership or modification of the utility transformer, enabling safer, standards-compliant connections. The method provides a practical framework for utilities and DER developers to evaluate grounding configurations and measurement points, ensuring protection coordination and code adherence in impedance-grounded systems.

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