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An Approach for Screening Distribution System Ground Fault Overvoltage (GFOV) in the Presence of Inverter-based Resources

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SUMMARY

Today, typical utility interconnection analysis related to grounding assume all Distributed Energy Resources (DER), regardless of type, have the characteristics of a synchronous generator. Most of the DER installed today are inverter-based and have very different behavior during fault conditions in comparison to rotating generation. Applying the old practices that were appropriate for non-inverter-based resources can result in unnecessary application of supplemental ground sources and/or unacceptable over-voltages that could damage both customer and utility equipment. A software tool was developed to allow utility engineers to screen inverter-based DER interconnections for effective system grounding and assist in selection of a supplemental ground source where necessary.
Instead of assuming the inverter system as either a Thevenin equivalent voltage source or a voltage controlled current source as in some commercial planning software, this tool models the inverter in a more realistic form and captures the inverter's operating boundary such as the maximum phase current and line-line voltage. The tool minimizes the data requirements from the users through automatically searching for worst-case scenario of the inverter's negative sequence behavior, so the screening study is possible before vendor-specific models become available for more detailed analysis using electro-magnetic transient simulations.

KEYWORDS

Distributed Energy Resource (DER), Ground Fault Overvoltage (GFOV), Inverter-based Resource (IBR), Negative Sequence Impedance, Symmetrical Components, System Grounding

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I. INTRODUCTION

Most North American radial distribution systems are four-wire, multi-grounded neutral systems with the substation transformer providing the primary system grounding source. Depending on the effective zero sequence impedance relative to the positive sequence impedance, a single line-to-ground fault tends to raise voltage on the un-faulted phases while collapsing voltage on the faulted phase. With too large a zero-sequence impedance relative to the positive-sequence impedance (a weak ground source), resulting ground fault overvoltage (GFOV) on the un-faulted phases can reach damaging magnitudes resulting in equipment failures. According to IEEE C62.92.1 [1], effective system grounding holds the GFOV magnitude to less than 80% of line-to-line voltage.

When the distribution feeder breaker opens, the zero-sequence grounding path provided by the substation transformer is removed from the feeder. When no generation sources are present on the feeder, this is an inconsequential event because the feeder is not energized when the breaker is open. However, when Distributed Energy Resources (DER) are connected to the feeder, there is the possibility that energization of the feeder could be maintained for a short time following separation of the feeder from the substation (Fig. 1). Utility DER interconnection practices, related to system grounding, are typically based on the assumption that DER have the characteristics of a synchronous generator and the software tools for modeling ground fault overvoltage assume a voltage source or constant current source (typical assumption for inverter-based) for the generator. Fundamental differences between inverter-based and rotating generation resources during fault conditions make it necessary to update practices and guidelines for assessing effective system grounding and applying grounding transformers (GT).

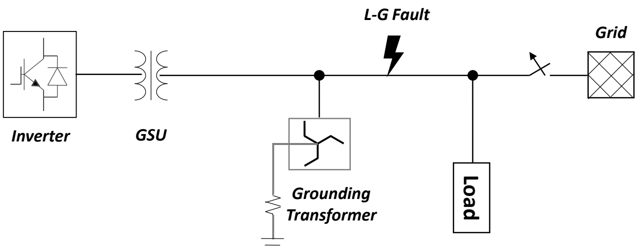


Fig. 1 Addressed GFOV scenario

A new software tool has been created to provide distribution and protection engineers with a convenient means to analyze grounding and over-voltages for the situation of an island energized solely by a three-phase, inverter-based DER during a line-to-ground fault; a situation that conventional short-circuit analysis software has not had the capability to appropriately analyze. The tool calculates the ground fault overvoltage using classic symmetrical component analysis and the commonly understood behavior of inverters operating in either grid forming or grid following control modes. This tool enables quick screening of DER applications to determine if expensive and tedious analysis using Electro-Magnetic Transient (EMT) software is required and help size a supplemental ground source.

II. INVERTER-BASED RESOURCE CHARACTERISTICS AND SYSTEM GROUNDING

Many utilities continue to use analysis practices that assume that inverter-based DER are a Thevenin equivalent voltage source with a defined positive sequence reactance. For fault current behavior and ground-fault over-voltages, grid following inverters can be more accurately characterized as constant current or constant power sources than as voltage sources (further discussion on inverters' voltage-limiting characteristics follows below). In the most typical grid following control strategy, constant current is regulated by the innermost control loop, with millisecond response. Setting the reference, or target value for this current regulator is a constant power regulator, forming an outer control loop that may have response on the order of tens of milliseconds. Therefore, the traditional approach to effective grounding is not applicable when inverters are the source of energization of an islanded feeder [2]. The source impedance criteria (X0/X1 and R0/R1) cannot be applied because the inverter sources, in the idealized sense, have infinite impedances. The broader meaning of effective grounding must be applied, and that means that the parameters of the entire islanded system must be considered, including loads. Unlike with synchronous generators, where load has little impact on GFOV magnitude, loads define the sequence impedances when inverters are the source [3]. A grounded-wye-connected, 3-phase load presents finite value of zero sequence impedances. If all loads on an inverter-based DER-energized island are connected phase-to-ground and are relatively well-balanced between phases, the zero-sequence and positive-sequence impedances of the system are approximately equal and there is no expected ground fault overvoltage, even without an explicit ground source included in the isolated system. This is because such loads are themselves adequate ground sources [4]. In situations where the generation-to-minimum-load ratio exceeds one and a fault does not exist, there is the potential for a power frequency TOV called a Load Rejection Overvoltage (LROV) though [5]. However, a LROV is not expected to be mitigated with supplemental grounding.

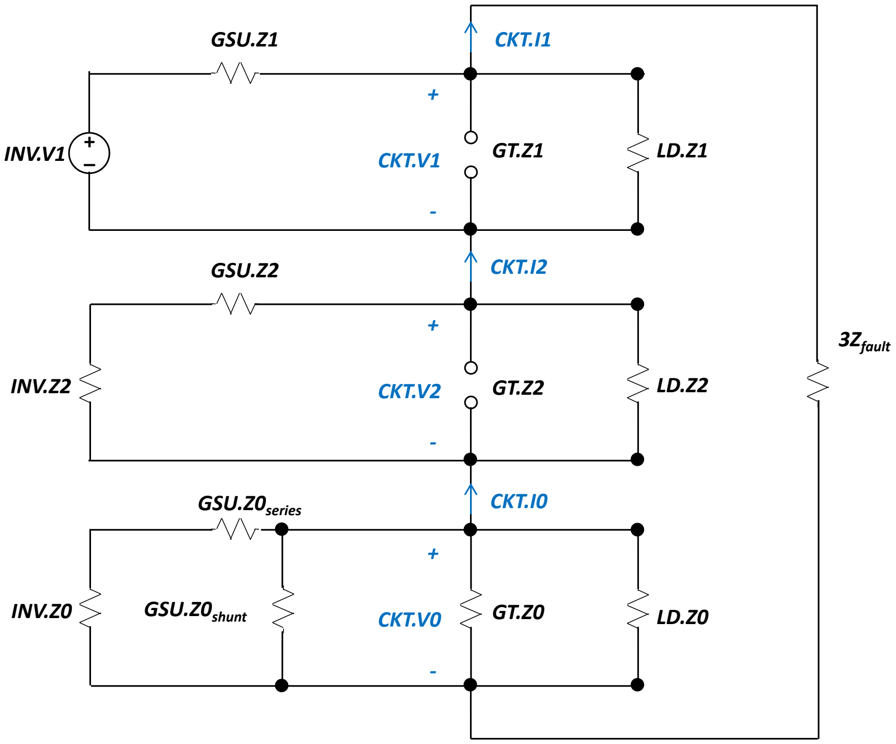
Today's inverters, typically based on solid-state switching devices such as IGBT, are susceptible to thermal breakdown and, therefore, must have the conduction current closely managed by the control algorithm. A well-designed inverter control often has several current limiting thresholds based upon its instantaneous, positive sequence, negative sequence, and phase currents. Among these, the limit on phase current is usually specified explicitly in the datasheet and the most relevant to fault analysis. Many commercial software tools model an inverter as a balanced current source based on this information. However, as it has been discussed, this balanced current contribution is often not reflective of the actual condition and can result in unrealistically high voltage values, which ignores the fact that an inverter is voltage limited.

Most inverter systems use Voltage Source Converter (VSC) topology which generates the desired AC voltage waveform by modulating a DC voltage. The maximum instantaneous voltage across two phases on the inverter AC side is therefore limited by the available DC voltage. Meanwhile, almost all inverter controls will have voltage limiting logic as those power electronic components are also susceptible to voltage breakdown. On this basis, an inverter is both current limited (on phase) and voltage limited (on phase-to-phase) energy source. These operating limits are important to include in any modeling effort.

The negative sequence impedance presented by the DER can have a substantial impact on the GFOV. It must be noted that such negative sequence impedance is dependent on the control algorithm implemented and may change in a non-linear fashion throughout the transient event. For example, an inverter with dynamic grid support function may be designed to supply negative sequence current in proportion to the system negative sequence voltage which manifests as an equivalent negative sequence impedance of 1pu. However, when the resulted current hits a certain limit and must be clamped, the negative sequence impedance can increase to a rather large value. This dynamically varying impedance over a wide range is one reason that most inverter manufacturers do not publish a single value for negative sequence impedance, and assuming a time invariant negative sequence impedance has the potential to underestimate the overvoltage. An analysis approach that does not assume a fixed negative sequence impedance but chooses a worst-case negative sequence impedance will yield a more conservative estimate of GFOV.

III. SYMMETRICAL COMPONENT ANALYSIS

A sequence network is shown in Fig. 2 that represents the situation depicted in Fig. 1 The sequence impedances for the generator step-up transformer (GSU), the grounding transformer (GT), and the load (LD) are relatively easy to acquire. However, the parameters of the inverter's equivalent controllable voltage source in the positive sequence, and impedances in the negative and zero sequences are to be determined through more dedicated approach that will be described.



V – Voltage, **I** – Current, **Z** – Impedance
0 – Zero sequence, **1** – Positive sequence, **2** – Negative sequence
CKT – Circuit, **GSU** – Generator Step-Up Transformer
INV – Inverter, **GT** – Grounding Transformer, **LD** – Load

Fig. 2 Sequence network

After all parameters as shown in the sequence network are obtained, the sequence network can be readily solved using basic circuit theory. Equations (1)-(8) explain the derivation of the circuit voltage and current in each sequence network. In these equations, each variable has a prefix to indicate if the variable represents an electrical quantity for an element or for the overall circuit (i.e., CKT). Please refer to Fig. 2 for more explanations of the variable names.

CKT.Z1=1/(1/GSU.Z1+1/GT.Z1+1/LD.Z1)	(1)
CKT.Z2=1/(1/(INV.Z2+GSU.Z2)+1/LD.Z2)	(2)
$CKT.Z0=1/(1/(INV.Z0+GSU.Z0_{series})+1/GSU.Z0_{shunt}+1/GT.Z0+1/LD.Z0)$	(3)
CKT.I1s=INV.V1/GSU.Z1	(4)
$CKT.V1=CKT.I1s/(1/CKT.Z1+1/(CKT.Z2+CKT.Z0+3*Z_{fault}))$	(5)
$CKT.V2=-CKT.V1*CKT.Z2/(CKT.Z2+CKT.Z0+3*Z_{fault})$	(6)
$CKT.V0=-CKT.V1*CKT.Z0/(CKT.Z2+CKT.Z0+3*Z_{fault})$	(7)
CKT.I1=CKT.I2=CKT.I0= $CKT.I1s*CKT.Z1/(CKT.Z1+CKT.Z2+CKT.Z0+3*Z_{fault})$	(8)

It shall be noted that the winding connection of the GSU transformer is important as it not only defines the zero-sequence impedance, but also affects the ability of the inverter to "see" the voltage on the high side of the transformer [6]. For example, a Yg/Yg GSU transformer yields a zero-sequence continuity as shown in (9) and permits the inverter to see the same phase-phase and phase-to-ground voltage on the distribution feeder side, neglecting saturation. However, a Yg/Y (Y on the inverter side) GSU transformer offers no zero-sequence continuity, as shown in (10), and cause the inverter to lose the ground reference to the distribution feeder unless the neutral point is explicitly accessible for instrumentation.

$GSU.Z0_{series}=GSU.Z_{leak}$, $GSU.Z0_{shunt}=\infty$	(9)
$GSU.Z0_{series}=GSU.Z0_{shunt}=\infty$	(10)

In most applications, the zero-sequence impedance of the inverter is infinite as it does not supply zero-sequence current. For applications where zero-sequence current is supplied through GSU (e.g., Yg/D with D on the inverter side) or additional zero-sequence sources, one can simply consider using the GSU or the grounding transformer to model. If the inverter does provide zero-sequence current through the fourth leg, a reasonable value of INV.Z0 should be selected based on its actual control design. To solve the network equations, the most important parameters remaining to calculated are the inverter's controllable voltage source (INV.V1) and its negative-sequence impedance (INV.Z2). Determining these values is shown in the next section.

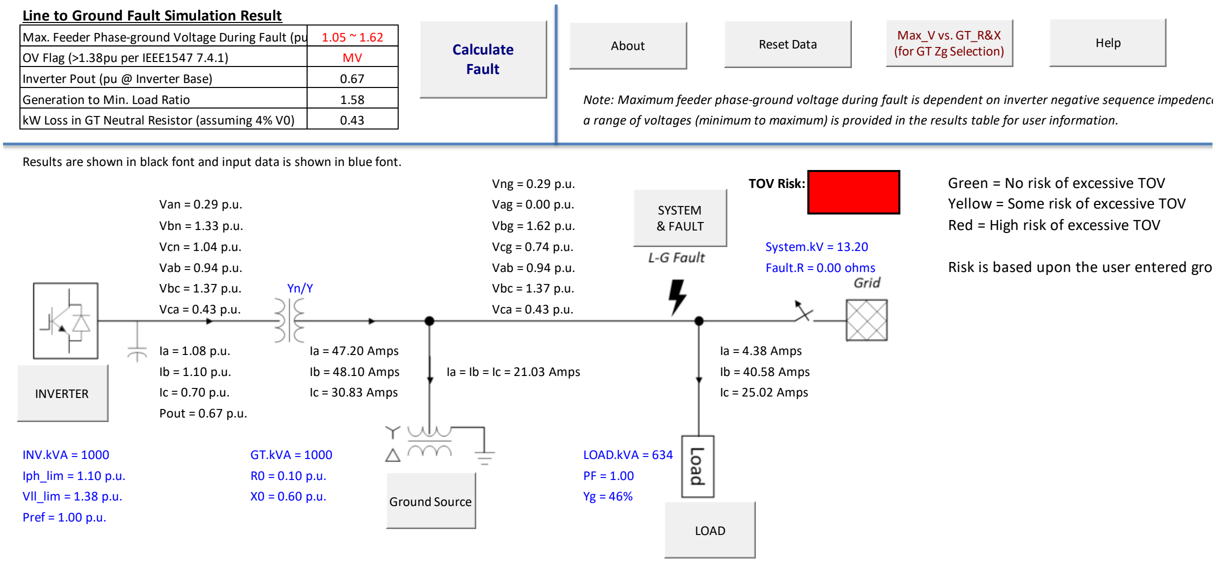


Fig. 3 Screenshot of the tool

IV. Software Implementation

Performing a symmetrical component analysis to estimate GFOV can be an effective alternative to using commercial short circuit modeling tools. However, doing this by hand or building code to perform the analysis can be time consuming. This section describes the software implementation of the symmetrical component analysis.

An Excel-based Inverter-based Supplemental Ground source Tool (ISGT) was created upon the above discussion to provide a quick way to assess overvoltage risk of an inverter powered network during ground fault. Fig. 3 provides a screenshot of the home page of the tool, while Fig. 4 shows the input from of the inverter parameters including the operation limits of voltage and current that are critical to proper representation. Although this tool was designed to be simple with minimal data entry needs, it's worth the effort to provide the circuit data as accurate as possible. For example, the load parameter form (shown in Fig. 5) asks for the minimum concurrent load (for better estimation of LROV), average power factor (which affects the search for the worst-case inverter negative sequence impedance), and the percent of grounded load (to properly capture the zero-sequence impedance rendered by load). While the computation doesn't require balanced load (i.e., equal positive and negative sequence impedances), most utility users consider it as the default case.

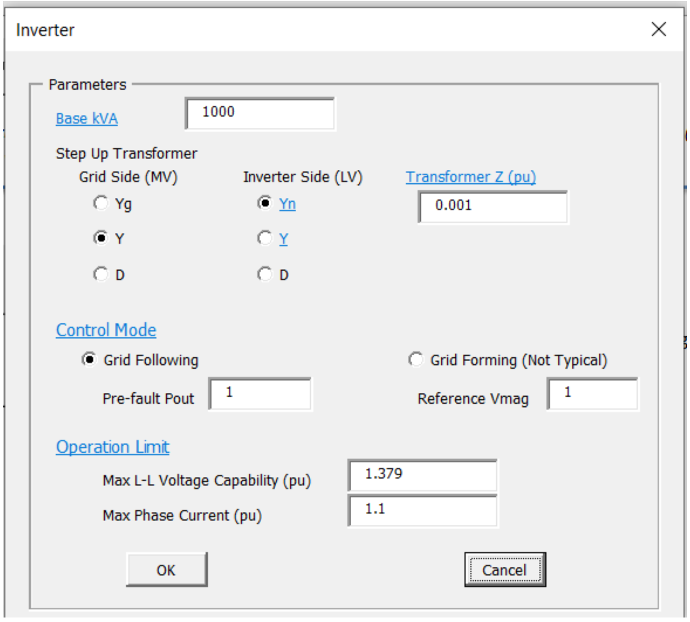


Fig. 4: Inverter parameter form

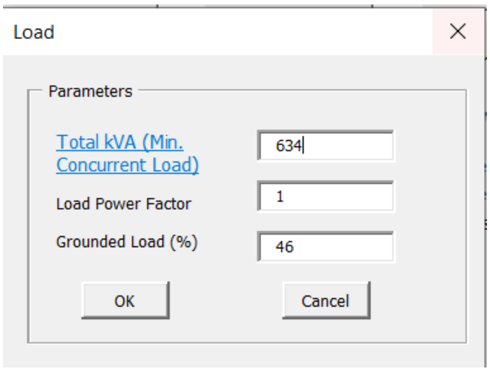
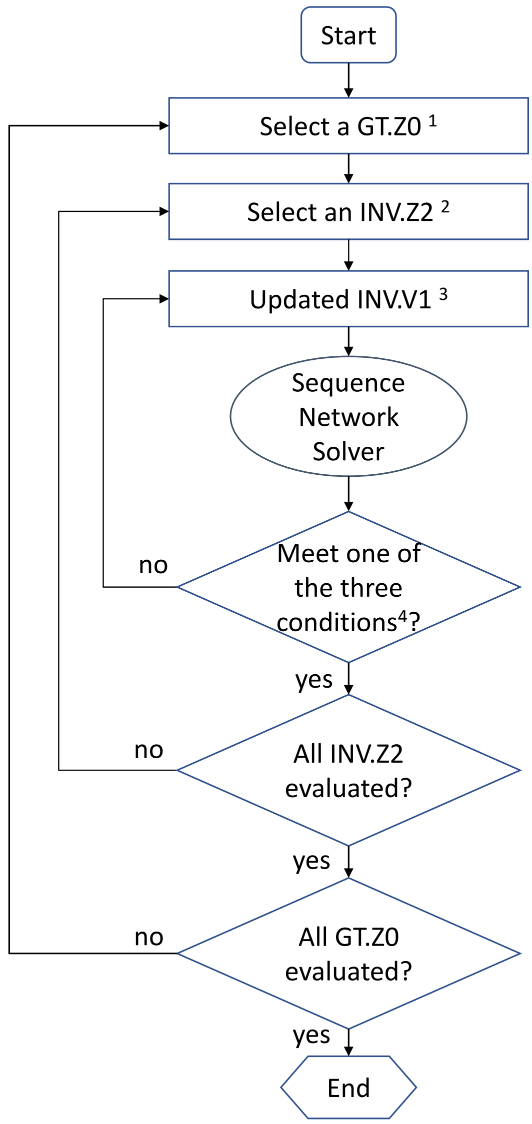


Fig. 5: Load parameter form

Fig. 6 illustrates the calculation procedure implemented in the tool. There are three iteration loops involved. The most inner loop searches for the proper inverter output when either of the three conditions is satisfied. In certain fault cases, the inverter can still fulfil its normal control objective such as power regulation without violating either current or voltage limitation. Otherwise, the inverter may hit its current limit or voltage limit, whichever comes first.



1 Sweep the inverter negative sequence impedance in a wide range (magnitude from less than 1pu to infinite, and angle from purely capacitive to resistive to purely)

2 Sweep the grounding transformer impedance in a wide range (automatically selected by the software using resulted GFOV)

3 An iterative algorithm is implemented to mimic a close-loop feedback inverter control that tries to meet the nominal control objective until either a voltage or current limit is hit. More specifically, the inverter positive sequence voltage, INV.V1, is raised or lowered in a numerically-stable way depending on the feedback error until certain convergence criteria satisfy

4 *Condition 1: Inverter still achieving its nominal control objective*

(INV.P=P_{ref} (if Grid Following) **OR** INV.V=V_{ref} (if Grid Forming)) **AND** (INV.I_{abc} <= I_{Lim}) **AND** (INV.V_{LL} <= V_{Lim})

Condition 2: Inverter hitting current limit

(INV.I_{abc} = I_{Lim}) **AND** (INV.V_{LL} < V_{Lim})

Condition 3: Inverter hitting voltage limit

(INV.I_{abc} <= I_{Lim}) **AND** (INV.V_{LL} = V_{Lim})

Fig. 6: Analysis flowchart

The calculated result from each iteration is based on an assumed inverter negative sequence impedance (INV.Z2). As discussed earlier, given its operation-condition-dependent and time-variant nature, it is plausible to vary the inverter negative sequence impedance in a reasonably wide range and search for the worst-case scenario to render conservative results to users for screening purposes.

Hence the tool adds an iteration loop on INV.Z2 (with varying both magnitude and phase angle) and reports out the maximum overvoltage level.

In the case when a grounding transformer is to be selected, the tool adds another iteration loop to also evaluate different transformer impedances and calculate the worst-case feeder overvoltage for each R and X combination of the impedance.

Fig. 7 shows an example contour map of the maximum feeder overvoltage versus zero sequence resistance and reactance of the grounding transformer where the region below the dark green maintains GFOV below 1.37 p.u.

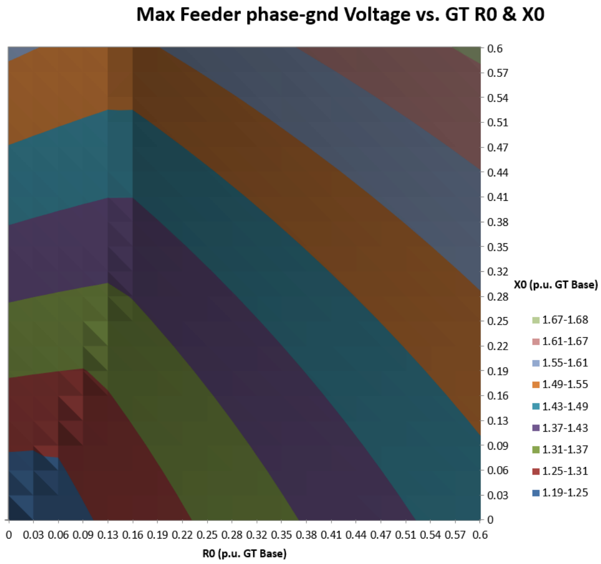


Fig. 7: Contour map of overvoltage magnitude

V. Verifying Results

Although software tools designed to perform power flow and protection analysis are improving their ability to model inverter-based resources, the current tools are still lagging in providing accurate overvoltage information when there is a loss of ground and primary voltage source. An analysis on a small distribution feeder, shown in Fig. 8, , was performed using a popular distribution power flow tool to demonstrate the erroneous results that can be obtained. The feeder model represents a 100 kVA three-phase inverter with fault current contribution equivalent to 125% of its rated current, a 100 kVA three-phase line-to-ground connected load operating at unity power factor, and no supplemental ground source.

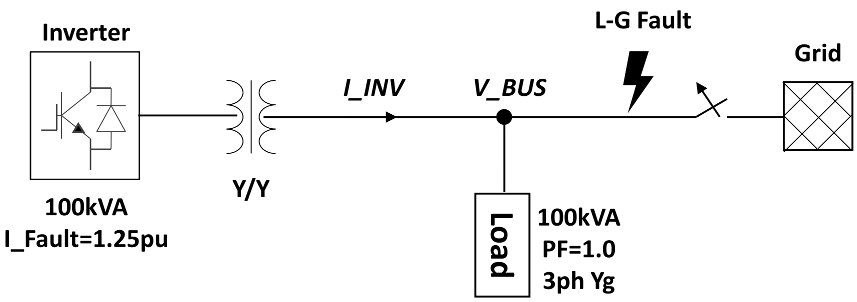


Fig. 8: Sample distribution feeder

Table I shows the results from a commercial software tool for a line-to-ground fault followed by a loss of system ground at the substation. The inverter in this example is modeled as a constant current source and maintains balanced current across all phases during the fault. Exceptionally high line-to-ground voltages (up to 2.2 p.u. of nominal) and line-to-line voltages (up to 3.33 p.u.) are obtained from the simulation.

While a few commercial software vendors have adopted a voltage-dependent-current-source model (that uses a lookup table to map the inverter terminal voltage to its current injection) [7][8] to represent the fault behavior of an inverter-based source, the applicability of such a model is still questionable.

Table I: Fault analysis results from a commercial software

Phase	I_INV	VLN_BUS
A	1.25 p.u. / 180 deg.	1.25 p.u. / 65 deg.
B	1.25 p.u. / 60 deg.	2.17 p.u. / -39 deg.
C	1.25 p.u. / -60 deg.	1.25 p.u. / 169 deg.

Attaining these high voltages in a real-world inverter design (both hardware and software) is not practical. For comparison, this same analysis was performed in ISGT with an assumed line-to-line voltage control/protection limit of 1.38 p.u. that has been derived from discussions with inverter vendors. The maximum line-to-ground voltage on the medium voltage bus with the worst-case inverter negative sequence impedance is no more than 1.25 p.u. This simple example demonstrates the issue with current commercial tools and the improved results when using the more reasonable inverter representation of ISGT.

In addition to verifying ISGT results against commercial power flow and protection analysis tools, an electromagnetic transient (EMT) analysis with a detailed generic inverter model was performed as a comparison to ISGT. The inverter model considers the switching transient, instantaneous current clamping, fundamental frequency over-current and overvoltage protection, and islanding detection. While all these protective functions have significant impact to the response speed of the inverter in detecting fault and tripping, the maximum overvoltage on the medium voltage feeder during ground faults is recorded within the first few cycles before the protection action for this comparison. The EMT analysis involved performing sensitivities on generation to load ratio, the interconnection transformer ground connections, with/without a supplement ground source, and the % line-to-ground minimum concurrent connected load. Fig. 9 shows a sample of the results for a Yg/Yg interconnection transformer, no supplemental ground source, and 100% line-to-ground connected load. The difference in peak line-to-ground voltage ranges from 3% to 10%. Other cases including supplemental ground sources and with varying levels of line-to-ground connected load resulted in differences ranging from 1% to 30%. It must be noted that as a screening tool, ISGT aims to minimizing the initial data requirement and searching for the most conservative result for risk assessment. Whenever potential risks are identified, it is recommended to perform detailed EMT simulations.

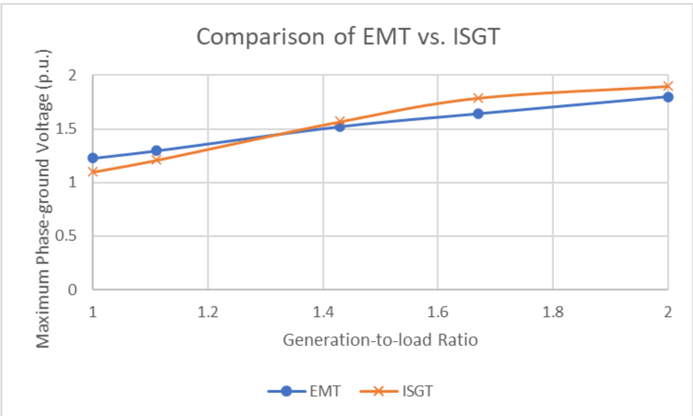


Fig. 9: Sample comparison results between EMT analysis and ISGT

VI. CONCLUSIONS

Assessing system grounding in the presence of inverter-based generation is among the most challenging issues encountered by distribution utility engineers. This paper illustrates a practical approach to determine the potential for ground fault induced temporary over-voltage (TOV) that exceeds acceptable limits and shows a software implementation of the approach. The software tool takes minimum input data that a DER developer can usually receive from the vendor or extract from the datasheet and iteratively solves sequence network to find the worst-case TOV result. Using the color-map generated by the tool to illustrate the TOV level versus the grounding impedance, the users can quickly select suitable impedance (resistance and reactance) to achieve effective grounding. The tool enables utility engineers dealing with DER interconnections to quickly screen for potential TOV risks and determine if further detailed EMT analysis is necessary. The results from the software have been compared to EMT analysis and commercial power flow tools typically used for TOV assessments with favorable outcomes. The software enables engineers to select a grounding transformer X and R that appropriately mitigates the over-voltage.

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