Single-Phase Open Detection in the Presence of Distributed Energy Resources

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***Abstract*— This paper deals with the subject of single-phase open detection on distribution circuits, in the presence of DERs, when the location of the SPO is arbitrary. It is demonstrated that it is nearly impossible to reliably detect all such SPOs based on conventional relaying. The best option, albeit imperfect, is zero-sequence current relaying. Some potential future options are also discussed.**

***Index Terms*—Islanding Detection, Single Phase Open, Distributed Energy Resources, Negative Sequence Relaying.**

I. Nomenclature

DER	Distributed Energy Resource
POI	Point of Interconnection
SPO	Single Phase Open

II. Introduction

SINGLE phase opens (SPOs) occur when only one phase of a three-phase circuit is isolated from the main utility voltage source. Fuses are probably the devices most often responsible for SPOs, but any form of switch or breaker capable of independent pole operation can form an SPO, and SPOs also form because of broken wires or loose connections.

Recently concerns have arisen that distributed energy resources (DERs), especially photovoltaic (PV) plants connected to an electric power system (EPS) through an inverter, may contribute to energization of an open phase downstream from an SPO. There was considerable discussion of this topic during the recent development of the version of the IEEE 1547 standard that went to ballot this year.

DERs are expected to incorporate unintentional islanding detection [1], but when an SPO forms on a three-phase circuit upstream from a three-phase DER, the DER is not islanded. Two phases are still connected and thus may still exhibit near-nominal voltages, but more importantly, islanding detection means that operate by trying to "push" the frequency of the island will not detect an SPO because the DER will not be able to change the frequency on the two still-closed phases. Thus, "anti-islanding" will not detect most SPOs.

The issue of SPO detection right on the terminals of the transformer, or without DER, has been addressed by others [2]. The purpose of this paper is to discuss the difficulties involved in SPO detection with DERs, when the SPO location on the circuit is arbitrary. The impact of transformer configuration on SPO detection, IEEE 1547 considerations, and potential mitigation strategies are discussed.

III. Voltage Downstream From an SPO

A. Voltage reconstruction downstream from an SPO

Intuitively one might expect that an EPS would be "cold" downstream from an SPO, because by definition the opened phase has been disconnected from the main utility voltage source. However, this is not always true in three-phase systems because of phase-phase coupling (also known as "voltage reconstruction") by transformers, motor loads, and to a lesser extent delta-connected loads. In this paper we will consider the voltage reconstruction properties of two common transformer types used with DERs: YG:d, and YG:yg.

1) Voltage reconstruction with YG:d transformers

Consider the diagrams in Figure 1 of a YG:d three-phase transformer with an SPO on phase C.

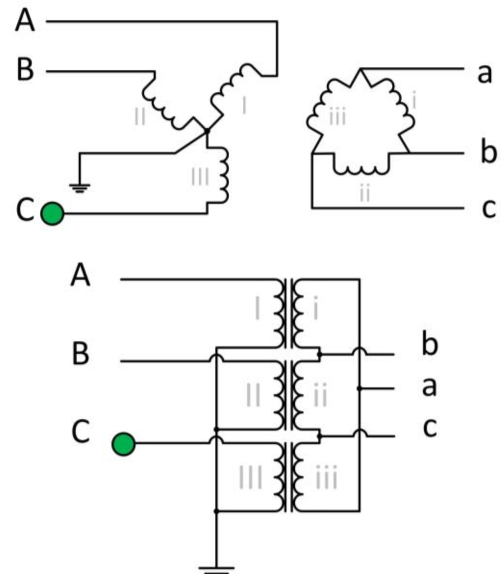

Figure 1. A YG:d distribution transformer with an SPO on phase C.

Phases A and B still see the nominal voltage, and thus coils I and II transform that nominal voltage to coils i and ii. Summing the voltage vectors around the delta (KVL), the voltage on coil iii must be the same as it was prior to the SPO, and this nominal voltage is transformed back across to coil III.

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Thus, when the transformer is lightly loaded, the YG:d transformer holds the voltage downstream from the SPO at essentially the nominal voltage, even when there is no DER.

The addition of load to the transformer modifies the situation because coil III, and thus coil iii, cannot carry any current or power due to the SPO. This means that a) all of the power is carried by the other two sets of coils, and b) there will be a large zero-sequence current flowing on the YG side of the transformer. Due to the resulting increase in voltage drops across the circuit impedances and the transformer itself, the level of voltage reconstruction below the SPO drops when the transformer is loaded.

Figure 2 shows a MATLAB/SimPowerSystems test circuit used to obtain SPO results for different transformer configurations. The circuit models a 13.8 kV four-wire multigrounded-neutral distribution circuit and includes constant-impedanceload, motor load, and a generic PV plant. The 3ϕ short-circuit strength at the PV POI is 12.2 MVA, so the short-circuit ratio at the POI is approximately 12. Figure 3 shows the results of two simulations on this circuit in which an SPO is formed on phase C at 1.5 s into the simulation. These simulations were performed with only resistive load and no DER. The lines with circle markers represent results using a 1 MVA, 5.75% Z, YG:d, three-leg core-type transformer loaded to 1% of capacity, and the lines with "x" markers are from a case where the same transformer was loaded to 100% of capacity. As expected, in the unloaded case, the voltage on the open phase is about 97% of nominal voltage and the two still-healthy phase voltages drop slightly from the pre-SPO case. In the loaded case, the voltage on the open phase drops to about 0.71 pu, and the voltages on the two still-closed phases separate because of the zero-sequence component.

2) Voltage reconstruction with YG:yg transformers

Whether voltage reconstruction will occur with a YG:yg transformer depends on the transformer's core structure. Figure 3 shows two configurations for core-type transformers: five-leg (top) and three-leg (bottom) [3]. A five-leg core provides return paths for the magnetic flux, as shown by the arrows in the top plot. The three-leg core does not; the sum of the three phase fluxes, or the "zero-sequence flux", must always be zero. If there is a single-phase open on one phase, say phase C, no exciting voltage is provided by the primary-side source. However, because the three leg fluxes must sum to zero, the flux in the core leg carrying the phase C coils is

$$\varphi_C = -(\varphi_A + \varphi_B) \qquad \text{Eq. (1)}$$

which is the same before and after formation of the SPO. Thus, for a YG:yg transformer utilizing a three-leg core, again almost the full voltage will appear on the open phase downstream from the SPO.

Figure 4 shows simulation results using the test circuit in Figure 2 but with a YG:yg transformer serving the load. In the fully-loaded case, the phase with the SPO still develops about 0.63 pu voltage, and the two still-connected phase voltages drop because they are now carrying roughly 50% more current,

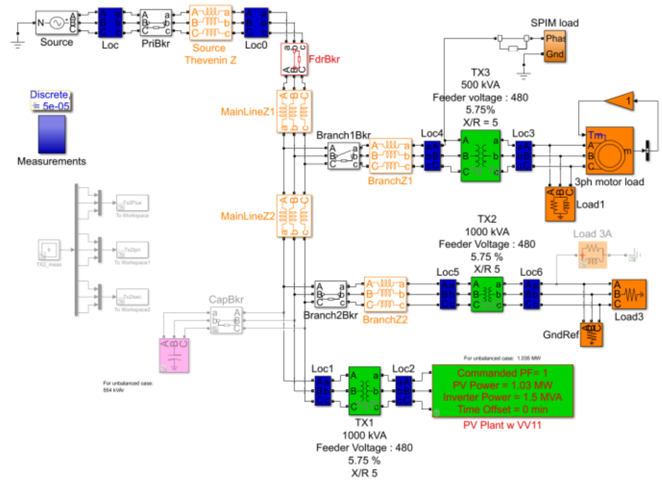

Figure 2. MATLAB/SimPowerSystems model used in this work. The circuit is a 13.8 kV circuit modeled in the sequence impedance domain. The model includes three-phase and single-phase induction machine load, impedance load (shown as purely resistive in the figure), and a PV plant.

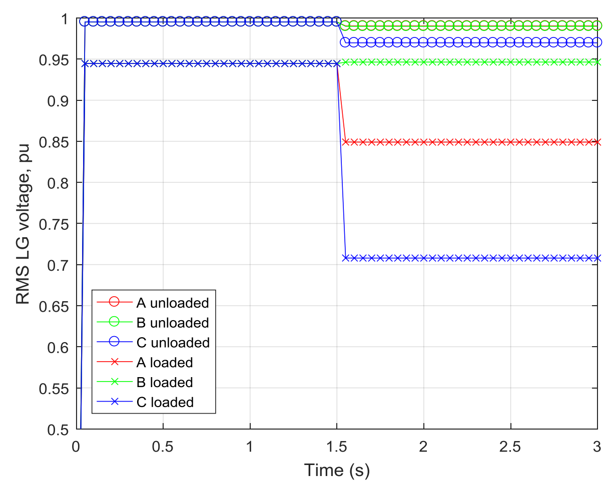

Figure 3. Simulation results with YG:d transformer, unloaded (circles) and loaded (x's).

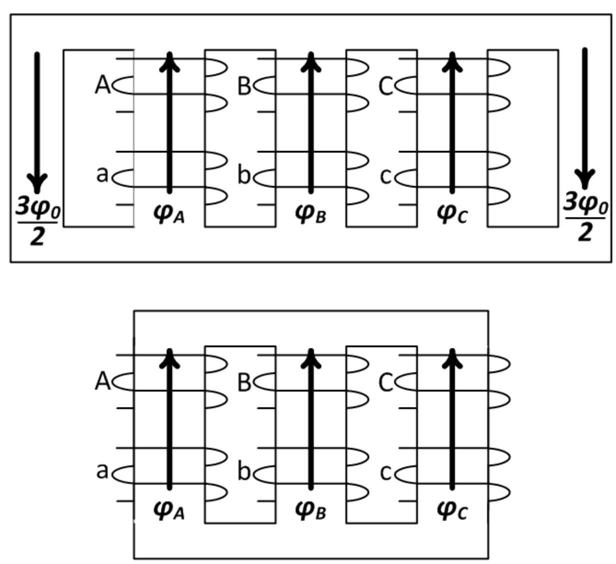

Figure 4. Diagram of the construction of a five-leg (top) and three-leg (bottom) core-type transformer.

and they separate because of the zero-sequence current flow (note that the degree of separation is reduced in this case because less zero-sequence current flows than was the case with the YG:d transformer).

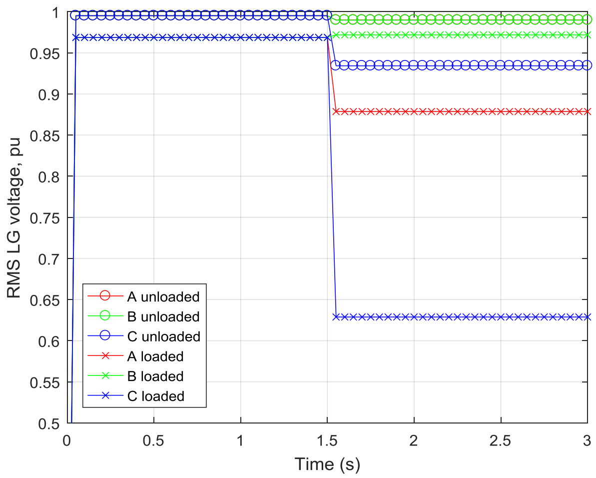

Figure 4. Simulation results with YG:yg transformer, unloaded (circles) and loaded (x's).

YG:y transformers, with the secondary windings ungrounded, are also relatively common in DER applications. The analysis above applies to the YG:y configuration; if the YG:y transformer is built on a three-leg core, Equation (1) still applies and voltage reconstruction still occurs on the open phase in the same way and with the same magnitudes as with a YG:yg configuration.

The point of the foregoing is that voltage reconstruction on the open phase downstream from an SPO is not a problem that is unique to DER, but instead exists in many three-phase circuits because of phenomena like those described here. This is one of many reasons why applicable rules require utility line workers to treat all phases as "hot" downstream from an SPO [4,5].

B. Voltage Reconstruction with DERs

We next consider the case in which instead of serving load the transformer serves a DER. Figure 5 shows a diagram of a DER sourcing current into a circuit with an SPO.

Symmetrical component analysis of this situation is challenging. Most texts that deal with this subject derive the sequence impedances seen looking into the terminals of the SPO, and it is found that essentially the three sequence networks are in parallel with one another [6,7]. However, the present situation includes sources at both ends (the utility source at one end and the current source of the DER at the other), and because the DER is a current source, it is imperative that the impact of loads also be included. The loads and circuit impedances essentially form a ladder network, and unbalanced load will lead to additional coupling between the sequence networks, all of which renders the analysis difficult. A full sequence component analysis is left to future work, and for present purposes simulation will be used to demonstrate the concepts. Regardless of winding configuration, when a transformer serves a DER instead of a

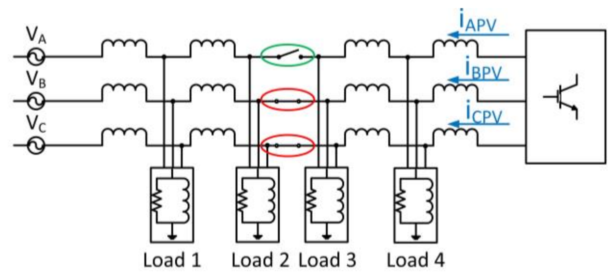

Figure 5. Diagram of a yg-connected distribution circuit with a DER and an SPO.

load, the unloaded analysis presented above would still apply to the case in which the DER is producing zero or near-zero power. In other words, a DER that is not in operation may attempt to start even when there is an SPO because it may detect near-nominal voltages at its POI.

When the DER is online, it is reasonably represented by a balanced three-phase power-controlled current source. When an SPO occurs, current flow is blocked at the point of the SPO, and the DER current on that phase must flow into the load downstream from the SPO. Thus, the voltage on the open phase will depend on the generation-to-load ratio (GLR) on the open phase downstream from the SPO.

1) SPOs with YG:d transformers and DER

Figures 6-10 show simulation results using the test circuit in Figure 2, with the DER (a PV plant in this case) and the constant-impedance load connected to the circuit via YG:d transformers. The DER is operating at unity power factor and constant power, all relays (27, 59, and 81 U/O) have been disabled, and the active anti-islanding is "off". The R-L load is balanced phase to phase. Two cases are shown: a case in which real and reactive power on the open phase downstream from the SPO have been balanced to within 1 kW and 1 kvar, and a case in which the GLR on the open phase is about 4.2:1. To balance the reactive power, a three-phase capacitor (not shown) was added to the circuit in Figure 5 between the DER and the SPO. Figure 6 shows the phase-ground voltages at the DER POI for both scenarios, Figure 7 shows the frequency of the voltage, and Figure 8 shows the symmetrical components of the voltage. Figure 6 shows that when the GLR = 1.00, there is no discernable change in the voltages, and Figure 8 verifies that the negative and zero sequence voltage components remain near zero. Figure 7 verifies that because two phases are still connected, the three-phase frequency measurement sees no detectable change. In the GLR = 4.2 case, the voltage on the open phase (C) rises when the SPO forms. The positive-sequence voltage (Figure 8) rises because the DER power is now being exported on two phases only so that the voltage rise increases, and a significant negative sequence voltage appears that actually causes the still-closed phase A voltage to rise above the voltage on open phase C. The zero-sequence voltage component remains small because of the grounding effect of the YG:d transformers. Figures 9 (phase currents at the PV POI) and 10 (sequence currents at the PV POI) indicate that zero sequence current relaying would easily detect the unbalanced case, but not the balanced one.

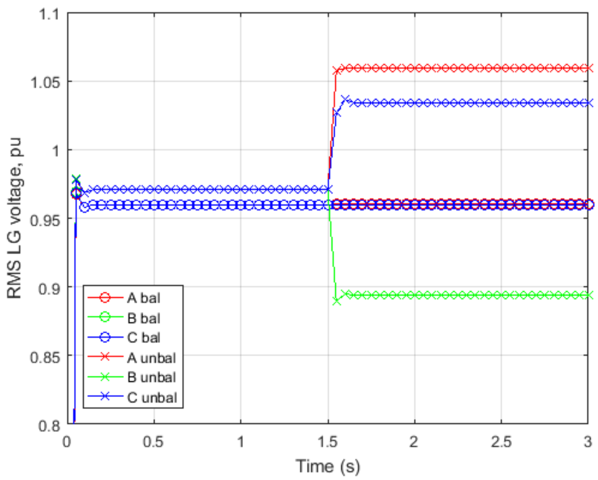

Figure 6. RMS L-G voltages at the DER POI during an SPO, for GLR = 1.00 (“bal”) and for GLR = 4.2 (“unbal”), with YG:d transformers.

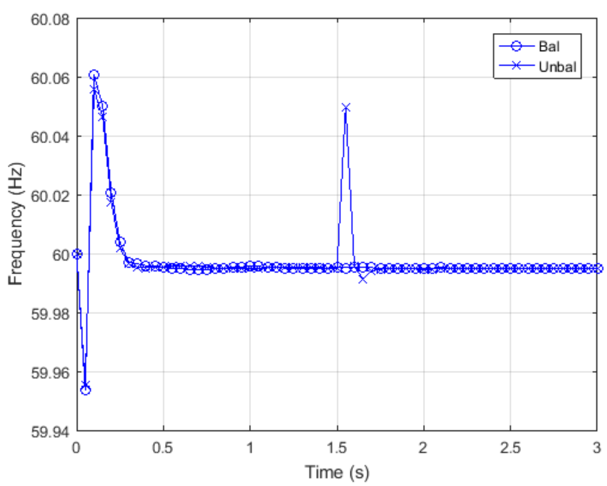

Figure 7. Frequency of the voltage at the DER POI during an SPO for GLR = 1.00 (“bal”) and GLR = 4.2 (“unbal”), with YG:d transformers.

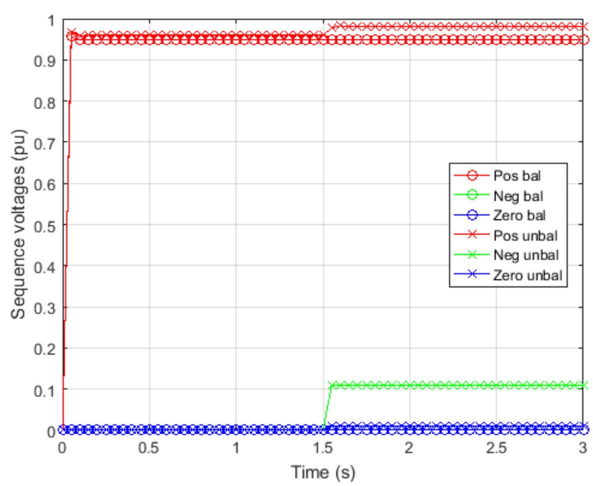

Figure 8. Sequence L-G voltages at the DER POI during an SPO for GLR = 1.00 (“bal”) and GLR = 4.2 (“unbal”), with YG:d transformers.

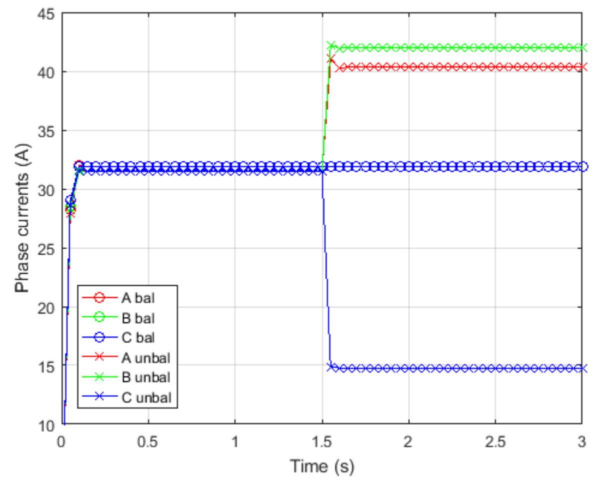

Figure 9. Phase currents at the DER POI during an SPO, for GLR = 1.00 (“bal”) and GLR = 4.2 (“unbal”), with YG:d transformers.

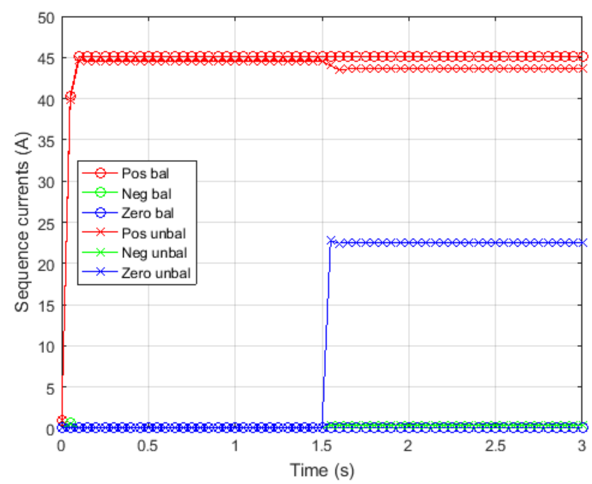

Figure 10. Sequence currents at the DER POI during an SPO, for GLR = 1.00 (“bal”) and GLR = 4.2 (“unbal”), with YG:d transformers.

2) SPOs with YG:yg transformers and DER

Figures 11-15 show results from simulations in which both the DER and the loads are connected to the distribution circuit by YG:yg transformers. As before, the DER operates at constant power and unity power factor, all relays (27, 59, and 81 U/O) have been disabled, and the active anti-islanding is off. The R-L load is balanced phase to phase. The same two cases are shown: GLR = 1.00 with the P and Q matched to within 1 kvar or kW, and a GLR ≈ 4.2 case. As before, in the very precisely matched GLR = 1.00 case (labeled “bal” in the figures), no change occurs in phase voltages, sequence voltages, or frequency. In the GLR = 4.2 (“unbal”) case, there is a bit more separation in phase voltages than in the previous case because the low-impedance zero-sequence path that existed with the YG:d transformers is not present when all of the transformers are YG:yg. Figures 14 (phase currents at the PV POI) and 15 (sequence currents at the PV POI) illustrate that, as before, zero-sequence current relaying would easily detect the unbalanced case, but the currents do not change appreciably in the balanced case.

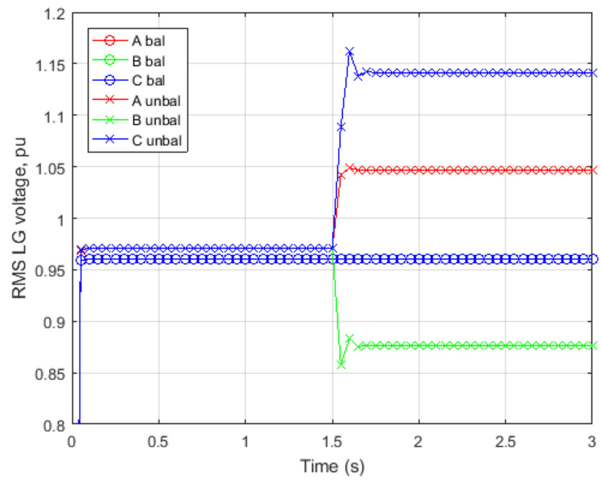

Figure 11. RMS L-G voltages at the DER POI during an SPO, for GLR = 1.00 ("bal") and for GLR = 4.2 ("unbal"), with YG:yg transformers.

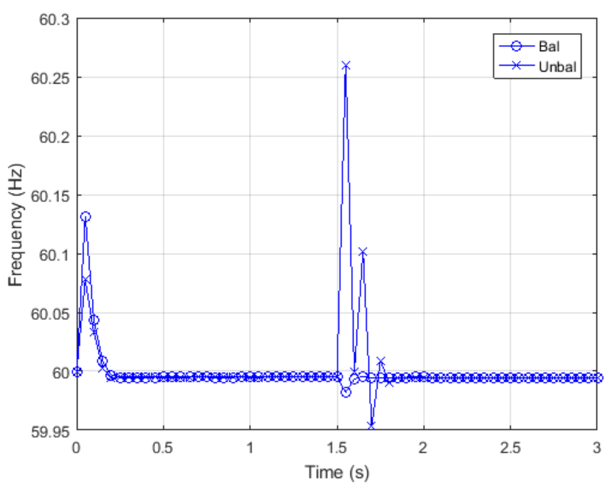

Figure 12. Frequency of the voltage at the DER POI during an SPO for GLR = 1.00 ("bal") and GLR = 4.2 ("unbal"), with YG:yg transformers.

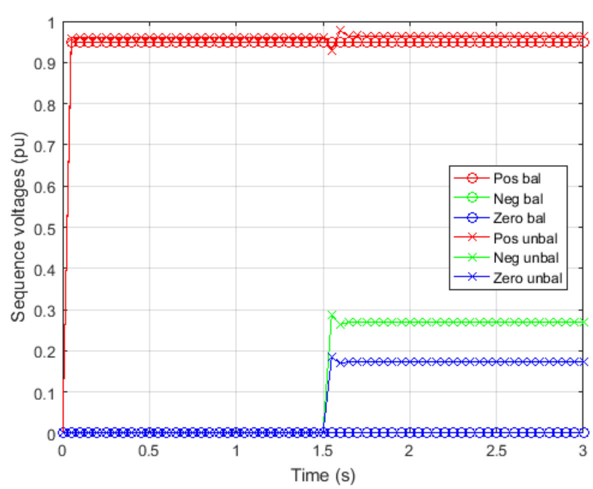

Figure 13. Sequence L-G voltages at the DER POI during an SPO for GLR = 1.00 ("bal") and GLR = 4.2 ("unbal"), with YG:yg transformers.

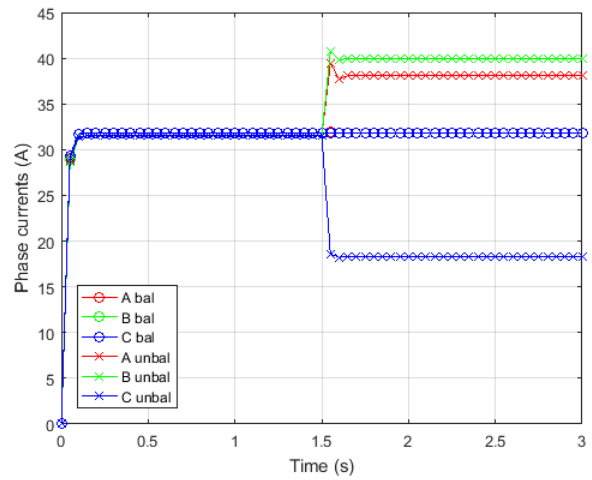

Figure 14. Phase currents at the DER POI during an SPO, for GLR = 1.00 ("bal") and GLR = 4.2 ("unbal"), with YG:yg transformers.

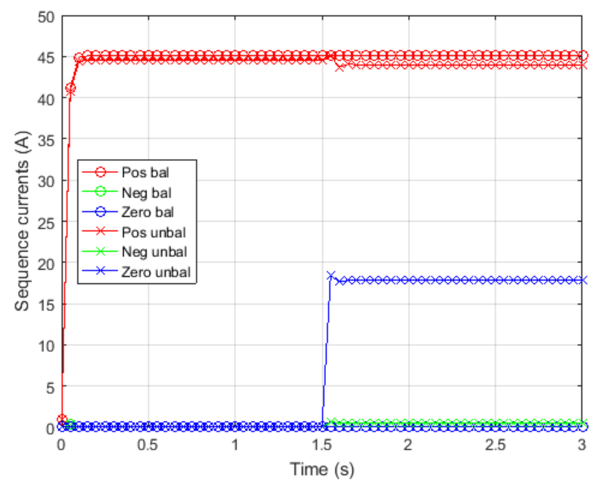

Figure 15. Sequence currents at the DER POI during an SPO, for GLR = 1.00 ("bal") and GLR = 4.2 ("unbal"), with YG:yg transformers.

3) SPO with motor load and DER

An additional set of simulations was run in which a portion of the load was replaced with a 200 hp three-phase induction motor, modeled using the SimPowerSystems built-in sixth-order model. Induction machines have reduced negative-sequence impedance relative to the positive-sequence value [8] and infinite zero-sequence impedance [9], and thus it was considered important to investigate their impact on SPO detectability. For the unbalanced cases including the motor load, the GLR was approximately 4.2:1 as before. All transformers in this case were YG:yg, with three-leg cores.

Figures 16-21 show the results. Figure 16 shows the LG RMS voltages in per-unit, Figure 17 shows the frequency, and Figure 18 shows the sequence voltages, all measured at the PV POI, for the GLR = 1.00 ("bal") and GLR = 4.2 ("unbal") cases. The voltage sag that occurs from about 0.5 to 1.5 s is due to the across-the-line starting of the large induction machine. The SPO forms at 3 s. Comparing Figures 11 and 16, the spread in the phase voltages is reduced in the motor-load case, and the phase C (open) phase voltage does not rise appreciably in the GLR = 4.2 case with the motor load. A key reason for this is that the motor current (shown in Figure 19) significantly increases on phase C, and the increased current draw on that phase partially counteracts the effect of the high GLR. The sequence voltages in Figure 18 also show this effect; comparing against Figure 13, the negative and zero sequence voltage components are lower in the motor-load case. Note also that the positive sequence voltage drops by about 0.06 pu from the pre-fault value in the motor-load case. That voltage drop is attributed to changes in the motor currents during the SPO event, which are plotted in Figure 19. Part of the difference between the impedance-load and motor-load cases is due to the location of the load in the circuit, as will be explained shortly.

The phase currents and the sequence currents at the DER POI are shown in Figures 20 and 21, respectively. Comparing Figures 21 and 15, it can be seen that when the motor load is included, the sequence currents at the POI do not change appreciably when the SPO forms, and thus SPO detection based on sequence currents is not likely to work in this case.

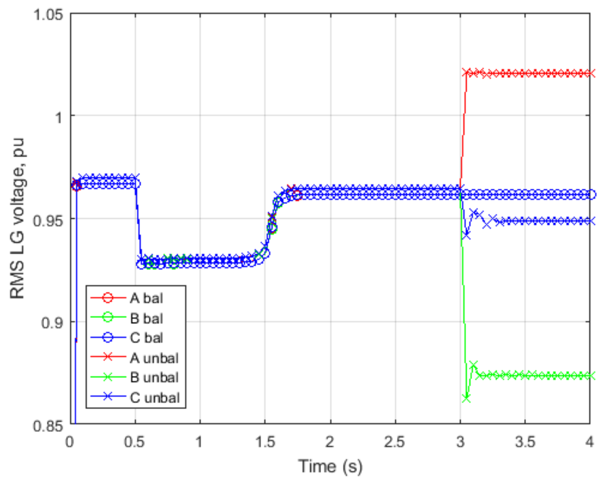

Figure 16. RMS L-G voltages at the DER POI during an SPO, for GLR = 1.00 (“bal”) and for GLR = 4.2 (“unbal”), with YG:yg transformers, motor load case.

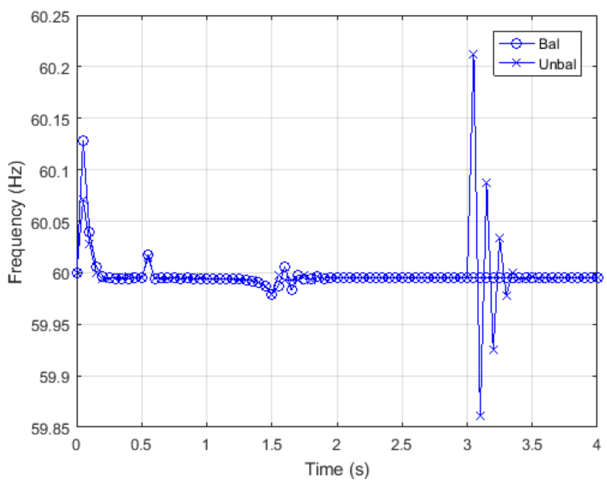

Figure 17. Frequency of the voltage at the DER POI during an SPO for GLR = 1.00 (“bal”) and GLR = 4.2 (“unbal”), with YG:yg transformers, motor load case.

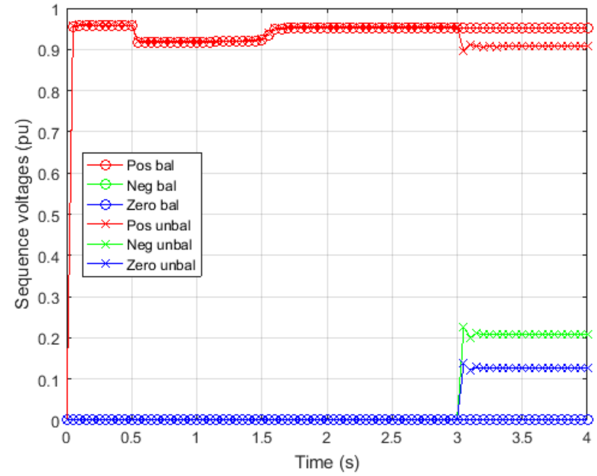

Figure 18. Sequence L-G voltages at the DER POI during an SPO for GLR = 1.00 (“bal”) and GLR = 4.2 (“unbal”), with YG:yg transformers, motor load case.

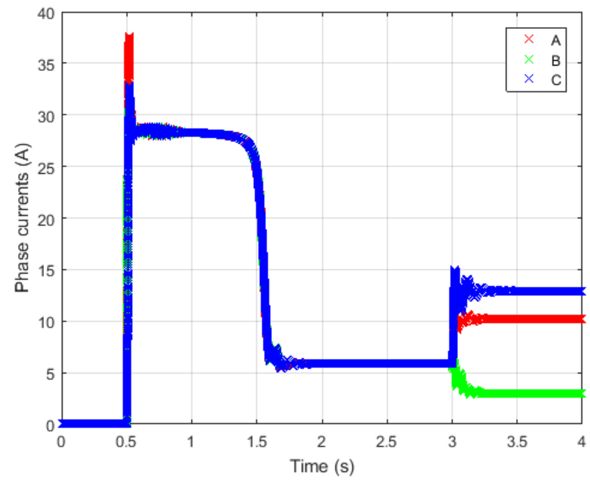

Figure 19. Induction motor phase currents during the SPO event.

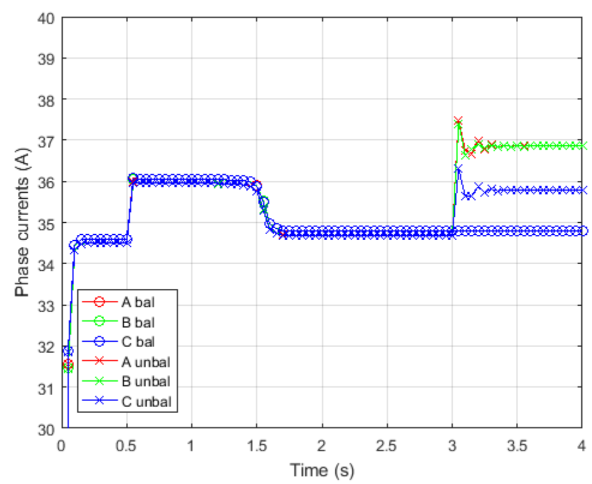

Figure 20. Phase currents at the DER POI during an SPO, for GLR = 1.00 (“bal”) and GLR = 4.2 (“unbal”), with YG:yg transformers.

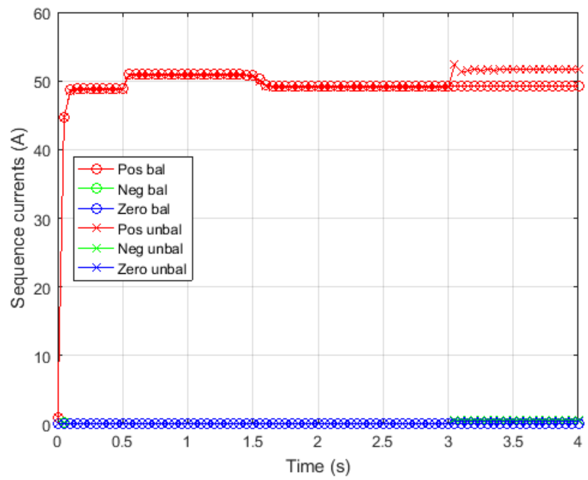

Figure 21. Sequence currents at the DER POI during an SPO, for GLR = 1.00 ("bal") and GLR = 4.2 ("unbal"), with YG:d transformers.

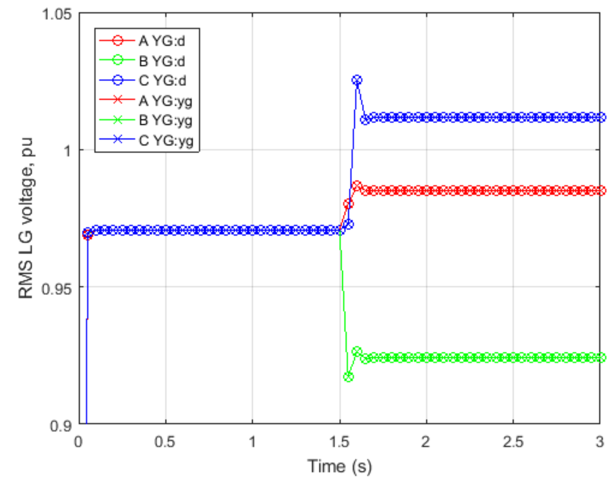

Figure 22. L-G RMS voltages for a case in which an SPO is formed right at the DER POI.

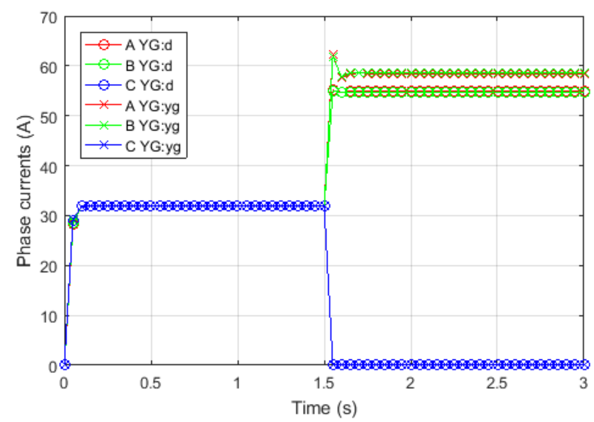

Figure 23. DER output phase currents during an SPO right at the POI of the DER.

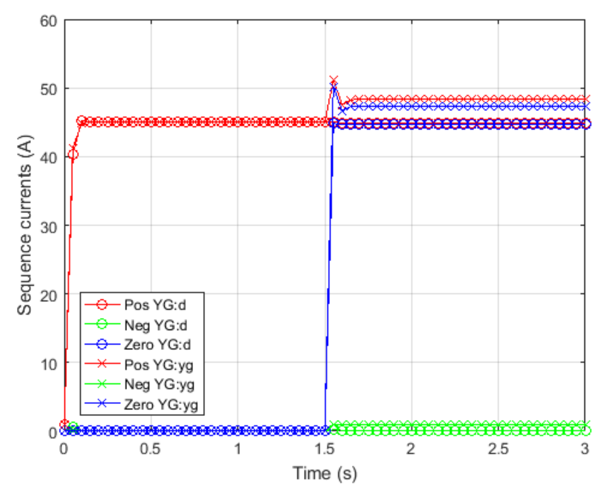

Figure 24. DER output sequence currents during an SPO right at the POI of the DER.

IV. SPO Detection in the New Version of IEEE 1547

Editorial note: the reader is cautioned that the discussion below applies to a draft version of an IEEE standard that has not yet been balloted and approved, and thus the content discussed here is subject to change.

During the drafting of the version of IEEE 1547 that went to ballot in early 2017, there was considerable discussion of what requirements should be placed on DERs for SPO detection and mitigation. Several field events came to light in which DER plants energized a circuit downstream from an SPO under conditions when this might not have been intuitively expected, and this elevated the status of SPO detection as a concern to be addressed.

One early suggestion was to treat an SPO as a single-phase island, in which case a 2 s detection time would have been required. However, ultimately it was decided that from the perspective of a three-phase DER, an SPO does not meet the definition of an island because it is not fully separated from the utility mains, and the "single-phase island" concept was discarded.

The decision that was ultimately reached was to require DERs to detect the formation of an SPO at the "reference point of applicability" (RPA), which is either the DER terminals or the PCC depending on conditions defined in 1547, but in either case includes essentially no load between the DER and the RPA. Figure 22 shows the results of a simulation of this case performed using the circuit in Figure 2, with the SPO applied at the high side of the DER transformer which is a three-leg core type configured either YG:d (circles) or YG:yg (x's). Because of the voltage reconstruction mechanisms explained in Section III-A above, the change in voltage after SPO formation is not especially large, so over/undervoltage or 3V0 relaying likely would not catch this case, and essentially the same results are obtained for both transformer configurations. However, Figures 23 and 24, which show the phase currents and sequence currents, respectively, at the DER POI, demonstrate that as expected there is a large change in phase and zero-sequence currents because of the loss of ability to export current on the open phase, and the SPO should be easily detected by zero-sequence current relaying.

V. Present and Future SPO Detection Options

Reliable SPO detection in the presence of DERs, when the location of the SPO on the circuit is arbitrary, is quite challenging. The foregoing results make it clear that if there is load between the DER and the SPO and the generation and load are precisely matched, there would be no change in voltage, frequency or current that can be detected by standard relaying means. Based on the analysis and results presented here, the best approach is zero-sequence current relaying, potentially backed up by negative-sequence voltage relaying.

Several different SPO detection approaches are being actively investigated. Impedance-based approaches can sometimes detect SPO via differences between phases, but these approaches do not work well when there are multiple DERs on the distribution circuit. One promising approach involves a power line carrier permissive (PLCP) signal that is normally intended for islanding detection. When an island is formed, the PLCP signal is lost and the DER can take appropriate action. In this case, if the PLCP signal is injected on all three phases and the downstream detection is performed on a per-phase basis, it may be possible to configure the system so that loss of the PLCP signal on one phase only would signify formation of an SPO, and again the DER can take appropriate action. While intuitively satisfying, this PLCP application could be rather challenging. Higher-frequency PLCP signals may electromagnetically or electrostatically couple from adjacent circuits or from healthy to open phases on the same circuit, so the signal may still be present downstream from the SPO. For very high-frequency digital PLCP systems, signals can be differentiated from one phase or circuit to another using digital data, but propagation of such signals to all endpoints on distribution networks remains challenging. Lower-frequency systems, like that described in [9], would be largely immune from these specific problems, but they have challenges of their own because the voltage reconstruction mechanisms described above for 60 Hz transformer operation would also apply to a system of this type, so again it is possible that under certain circumstances the PLCP signal could show up on the open phase downstream from the SPO. One possibility that is being explored is to take an impedance measurement of the circuit at the PLCP transmitter location by measuring the circuit's current draw at the PLCP harmonic frequency. A major phase-phase imbalance in this impedance could indicate the presence of an SPO, but it could prove challenging to set a threshold that simultaneously provides good detection and false trip immunity. Also, this approach requires tripping of all of the DERs on the circuit, not just those downstream from the SPO.

Approaches based on more advanced signal processing of the POI voltages and currents, and of their statistics, are also being explored. However, these share the same challenge as many other approaches: because the normal variability range of most parameters in distribution is relatively large, it is difficult to choose detection criteria that ensure reliable SPO detection without nuisance trips.

VI. Conclusions

In certain circumstances, SPO detection in the presence of DERs is a difficult challenge. In most cases one would have a generation:load imbalance that would lead to there being a detectable change in voltage, but if the GLR downstream from the SPO is sufficiently close to 1, there is almost no change at the DER terminals that can be detected. Motor load is especially problematic. At present, the best option is zero-sequence current relaying, potentially backed up by negative sequence voltage relaying.

VII. References

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VIII. Biographies

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Scott Perlenfein (M ,'12) was born in Burke, South Dakota (SD) in 1982. He received the Bachelor of Science in Electrical Engineering and Masters of Science in Electrical Engineering in 2008 and 2012, respectively, from South Dakota State University, Brookings SD. Currently he is a Senior Engineer at Northern Plains Power Technologies (NPPT) in Brookings. His research interests include MATLAB modeling and integration of power systems and distributed resources, including battery storage and photovoltaic systems; controls and synchrophasor-based protection in embedded systems; power electronics design for energy harvesting systems; and very low-power electronic systems.

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