Three-Phase Inverters and Short-Duration Overvoltages

Preliminary Testing and Analysis

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Technical Update, December 2014

EPRI Project Manager

A. Huque

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

THE FOLLOWING ORGANIZATION(S) PREPARED THIS REPORT:

ELECTRIC POWER RESEARCH INSTITUTE (EPRI)

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The following organization prepared this report:

Electric Power Research Institute (EPRI)
3420 Hillview Avenue
Palo Alto, CA 94304

Principal Investigator
B. York

Other Contributors

G. Rymer
B. Johnson
A. Huque

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ABSTRACT

This technical update documents an initial effort to recreate short-duration overvoltage conditions in a laboratory environment and to characterize the potential for distributed photovoltaics to contribute to over voltage. This effort separately addresses load-rejection overvoltage (LRO) and ground-fault overvoltage (GFO) with procedures for each. Both procedures have been initially vetted using EPRI's laboratory facilities in Knoxville and a single "off-the-shelf" commercial-scale inverter. Included in the report is a discussion of required test equipment, laboratory setup, data, results and analysis. Though additional work is needed to extend the analysis to additional inverter units and investigate more in-depth, the eventual goal of this effort will be to accurately inform modeling efforts and utility planning strategies with distributed photovoltaics.

Keywords
Distributed PV, Load Rejection Overvoltage (LRO), Ground-Fault Overvoltage (GFO), Transient Overvoltage (TOV), PV Inverters

EXECUTIVE SUMMARY

The potential for large concentrations of distributed photovoltaic (PV) systems to cause overvoltage conditions on distribution feeders is receiving industry attention. The question has particularly been raised in Hawaii with the rapid growth of inverter-connected residential PV systems. Recognizing that there is not a simple method to characterize inverter-driven overvoltage events, EPRI begin doing lab testing with PV inverters in its Knoxville Lab. The goal of this initial testing was to develop and demonstrate a laboratory test procedure suitable for evaluating the contribution of three phase inverters to short-duration overvoltage events. This report provides the draft test protocol and some initial laboratory testing results.

There are two specific cases, or overvoltage types, addressed by this report, these are load-rejection overvoltage (LRO) and ground-fault overvoltage (GFO). Given the preliminary nature of the test procedure, a single "off-the-shelf" inverter was used to conduct the initial evaluation. Though it is a single sample point, these test provide some insight into the potential for similar behavior in other inverters. The challenge in testing so far has been to isolate the inverter's contribution to the overvoltage and to separate the two events from one another. While isolation was possible for the LRO event, isolation of the behavior was not as conclusive for the GFO tests. Another important challenge is to identify a representative load and its inevitable interaction with inverters. Both the load's response, and immunity, to short-duration overvoltage will need to be better defined in the future.

While it's impossible to test every potential combination of inverters, load equipment, and feeder characteristics, the aim has been to gain beneficial understanding of typical inverter behavior in a controlled laboratory environment. The results included in this report should be considered preliminary, and evaluated as such. Key takeaways from this work are as follows:

- It is possible to create a test procedure that effectively evaluates LRO in isolation from other events
- It is much more difficult to isolate a GFO event from the LRO behavior
- Inverter control systems that are not designed to operate while islanded may have unpredictable output for a few cycles until they disconnect
- Secondary protection systems (such as anti-islanding) are the dominant protection mechanism that limit short-duration overvoltage and run-on time
- For the 3-phase inverter tested, and the test conditions, measured contributions to both LRO and GFO were well below expected upset and damage levels for utility or consumer equipment.

Knowing the potential, and likelihood, for distributed inverter-connected generation to create short-duration overvoltage is only part of the issue. Utility engineers must take the behavior of these units into account when specifying required protection systems and interconnecting equipment. They also need to consider other non-inverter connected distributed generation (DG). Grounding practices, maintaining a minimum load to generation ratio, clearing ungrounded DG and the application of grounding transformers may need to be considered. To address all these considerations in a system setting, test results for both LRO and GFO will need to lead back to modeling efforts.

In addition to the work completed so far in the Knoxville lab, EPRI is engaged with NREL, Hawaiian Electric, and SolarCity to conduct a battery of tests at the Energy Systems Integration Facility (ESIF). Once there are sufficient data from the testing we will identify and employ analytical methods to help utilities and the PV industry to evaluate specific cases. The long term objective is to identify interconnection practices and to make definitive recommendations for dealing with both the inverter's contribution to, and inverter's response to, GFO and LRO.

Recommendations for further research include:

- Extend the test procedure to determine the inverter response to less common faults
- Expand the testing base to include more inverters, including larger (100kW+ units)
- Dive deeper into the observed behaviors, in order to assess critical variables that influence the inverter's response, including that of the load.
- Further enhance the test procedure so that it can more clearly isolate LRO from GFO behaviors

In summary, we find that to address this broad range of options related to GFO and LRO additional testing, as well as, modeling and analysis are needed. A key future goal will be to incorporating the learning from testing and from simulations into commercially available software tools for everyday use by utilities.

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INTRODUCTION

Concerns with integrating distributed generation (DG) into the distribution system take several forms. Short-duration overvoltages, the main concern of this report, are event-based phenomena, occurring in seconds or less. However, the most common planning concerns in day to day operations are typically longer-term, "steady-state,"overvoltages that take place over minutes or hours. Examples of steady-state concerns are voltage rise at the end of a feeder, or thermal overloading of a transformer or line segment. In time frames of seconds to minutes, the concerns are typically related to normal variations in the DG output. A good example is a variation in PV output due to fast-moving clouds that may cause voltage changes and unplanned load-tap changer (LTC) operations.

Both the steady-state interactions and output variability have taken a front seat in day to day concerns for integration of distributed solar as well as DG in general. However, concerns over potentially unsafe levels of GFO and LRO also exist. Without a clear mitigation strategy post-deployment, concerns must be evaluated at the time of interconnection or before installation of DG. Consequently Load Rejection Overvoltage (LRO) and Ground Fault Overvoltage (GFO) concerns may prevent installation, irrespective to the robustness of the electric grid. Although planning issues have been the main determinate to establish physical hosting limits for feeders, there is also a need to better understand and consider GFO and LRO.

Motivation for Current Investigation

When considering the accommodation of high DG penetrations (especially distributed PV) there is a general wariness when it comes to GFO response and the DG contribution to LRO. The contribution to LRO or GFO from distributed synchronous generators has been well documented and generally understood throughout the past several decades. Inverter behavior is not that well defined or understood by power system engineers. Behavior of inverter-based generation is markedly different from synchronous machines and is also more dependent on control options taken by the designer. Some example of differences are:

1. Inverters are generally current-limited, rather than a natural voltage source
2. Inverters often have internal overvoltage protection which can cease operation often within 10's or 100's of microseconds after an event
3. Inverters typically generate power without a neutral to handle unbalance

Because of these differences conventional machine models are not easily adapted to reflect inverter operation. Moreover, the models of inverter-based DG designed for most hosting capacity studies are also not applicable, due to the short time-scale of LRO and GFO studies as well as the (un-modeled) ability for the inverter's internal protections to dominate the overvoltage response.

Because they generally don't have well defined models or tools necessary to analyze short-duration cases of inverter and grid interactions, distribution engineers are sometimes placed in an uncomfortable position. In order to be sure that safety and reliability of the system will not be negatively impacted the tendency is to be conservative about DG. Distribution engineers are compelled to error on the side of caution and to limit interconnections on certain feeders or require additional interconnecting equipment (such as grounding transformers or transfer-trip schemes). Decisions to limit deployment are often unpopular with developers or customers, and may be met with intense scrutiny from regulators, consumer advocates, or even legislative bodies.

Considering Prior Work

Many engineers and researchers have considered, and written about, the potential for synchronous DG to cause overvoltage. Several ways to mitigate or control overvoltage behaviors have been identified such as coordinating grounding practices and transformer selection [1]–[4]. Also, from the standards community, IEEE C62.92 has a very thorough discussion of effective grounding and its impacts on the surrounding systems [5]. However, for PV there has been resistance to any additional requirements and a challenge to prove the need. This has led to a number of industry whitepapers on this topic, [6]–[8]. Related, LRO and GFO were popular topics at this year's IEEE Power & Energy Society Transmission and Distribution Conference, with two educational seminars covering the area [9], [10].

Even with all of the overarching discussions, very little time has been devoted to laboratory testing of inverter behavior. Perhaps the most notable work in this area (specifically LRO) is credited to the Advanced Technology group at Southern California Edison (SCE) [11], [12]. Their testing specifically looked at the potential for certain PV inverters to contribute to LRO, and potentially damage end use or utility equipment. The authors tested one (single-phase) inverter (before and after software upgrades) and recorded the results. They noted the significant influence of the inverter's firmware, and overvoltage protection, including these needs:

1. Respond to instantaneous voltage levels rather than waiting on RMS calculations.
2. Control operation with algorithm for responses outside normal operating limits.

In a response to the mounting concerns over the short-duration behavior of inverter-based DG, an industry group was formed in 2013 to discuss both LRO and GFO. Comprised of representatives of inverter manufacturers, national labs, EPRI, and a number of consultants it is called the Industry Task Force on Effective Grounding (ITFEG). This group is currently attempting to devise test procedures intending to evaluate the overvoltage behavior of inverters. Their draft test procedure for LRO was directly modified for use in the testing in this EPRI project.

Project Objectives

- Observe key dynamics that govern inverter response to distribution faults
- Establish a baseline for future observations
- Vet test protocols that are technically grounded and reasonably recreate the expected physical phenomena
- Inform future modeling efforts for PV inverters for system planning and protection

Inverter Under Test

The same inverter model was selected for both the LRO and GFO tests. The model represents a commercially available, three-phase PV inverter with a 24kVA power rating. Typically targeted at commercial-scale PV installations, this size and configuration of PV inverter is rapidly increasing in popularity. Many large-scale installations also opt for this design over larger 200-500kVA units because they can be rack-mounted (which saves installation costs), have better energy harvest, and can be taken down for maintenance without disrupting the entire plant. The inverter unit does not have a line-frequency transformer, which further reduces size and weight over isolated units.

The unit under test is designated as a 277-V/WYE connected inverter. It can be connected to 480-V service, but must have a neutral connection brought to the inverter's terminals. In PV plant installations this limits the potential medium-voltage interface transformers to either delta-wye (ground) or wye (ground)-wye (ground). Additional inverter specifications are listed in the table below:

Table 1-1
Specifications on the Inverter Under Test

Floating PV Array?	Yes	Internal Transformer?	No
Maximum DC Power (kW)	30	DC Voltage Rating (V)	1000
# of MPPT Inputs	2	Minimum Voltage (V)	150
MPPT Voltage Range (V)	450-800	Nominal Output Voltage (V_{LL}-RMS)	480
Max DC Input Current (A)	66	AC Output Range (V_{LL}-RMS)	422-528
CEC Efficiency	0.98	Height (m)	0.665
Volume (m^3)	0.122	Length (m)	0.69
Weight (kg)	55	Width (m)	0.265
Power Factor Range	±0.8	IEEE 1547 Compliance	Yes

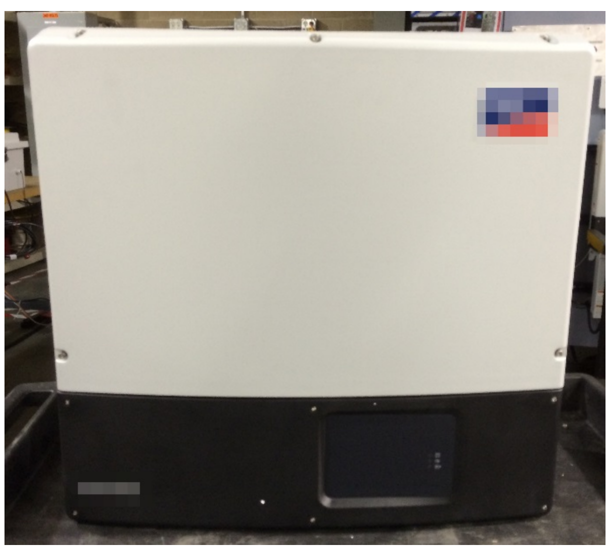

Figure 1-1
Three-phase Inverter used for LRO and GFO Testing

Other Required Equipment

EPRI Port-O-Sag

Originally designed to identify and investigate the behavior of sensitive loads and industrial process components, EPRI's Port-O-Sag, shown in Figure 1-2, is designed to create temporary sags or swells at its output from a utility line-level input. It does this by temporarily disconnecting the load from the utility input, and reconnecting it to the same input. This is done via a multi-tap isolation transformer. After the pre-determined duration of the disturbance, the load is returned to the primary input at full voltage.

Figure 1-2
EPRI's Port-O-Sag (Model PS200-3P-T-TM)

A simplified, single-phase schematic of the Port-O-Sag unit is shown in Figure 1-3. The unit makes is primary connection from input to output through a contactor (K1). Prior to creating the sag or swell a parallel IGBT (S1) is closed and the contactor (K1) is opened. To create an isolated sag or swell, S1 is opened followed immediately by the closing of switch S2 on a 9 microsecond delay. The timing of this procedure is summarized in the timing diagram in Figure 1-4. The depth of the sag is controlled by the selected tap on the front panel of the transformer unit. For our considered cases that voltage level was "ground" or 0% output. By connecting the inverter to the "load" side of the Port-O-Sag, a representation of a single-line-to-ground (SLG) fault can be created at its output terminals. This piece of equipment was utilized extensively in the GFO portion of the inverter testing.

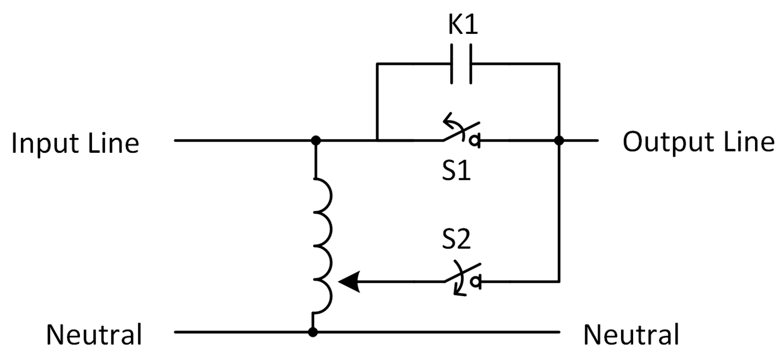

Figure 1-3
Port-O-Sag simplified single-phase diagram

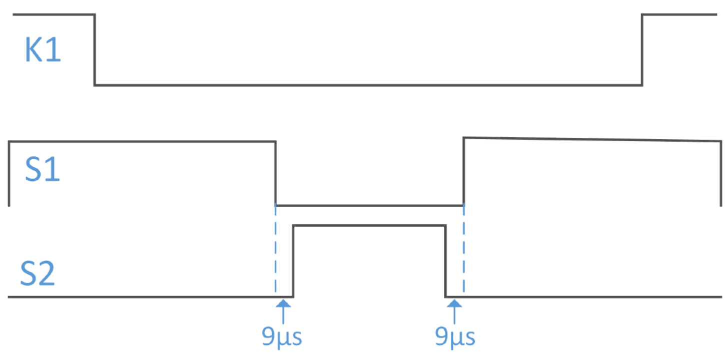

Figure 1-4
Port-O-Sag Simplified Timing Diagram

PV Simulator

Another key element of the test procedure was the use of a photovoltaic (PV) simulator as a supply for the inverter under test. The PV simulator is essential a switch-mode DC power supply that is programmed to emulate the behavior of an array at a given test condition. The selection of the array parameters for these tests was generic, with the following parameters:

Table 1-2
Parameters of Emulated PV Array

Parameter	Value
Open-Circuit Voltage	500V
Short-Circuit Current	27.5A
Max Power Point Voltage	448V
Maximum Output Power	11.9kW

Because the inverter under test has two independent dc inputs, tests conducted at 50% input power were conducted on a single supply (a Magna-Power LXI). The full-power tests required a supply with multiple output channels (an Elgar TerraSAS unit).

2
LOAD REJECTION OVERVOLTAGE (LRO)

Background

Originally considered as an issue with synchronous machines, the nomenclature of load rejection overvoltage has been extended to cover non-rotating types of generation. In a synchronous machine, if the output loading is removed suddenly, the output voltage may rise to unsafe levels due to excitation levels momentarily being too high for the remaining load [13]. Similarly, if inverter-based generation attempts to maintain a constant power output when the load is lost, it could cause an LRO event.

In a situation with a high-penetration of DG, especially PV, on a distribution feeder the potential for an LRO event revolves around the operation (or misoperation) of utility protective equipment. This could involve everything from the blowing of a lateral fuse to the operation of a feeder breaker in order to perform maintenance at a substation. As the amount of DG on the feeder is increased, its output may exceed the amount of load available on that portion of the circuit, leading to backfeed onto another part of the feeder or onto subtransmission. The protective element that operates (either fuse or breaker) then isolates the DG from a portion of its local load.

If an overvoltage event results, the concern is that other surrounding loads (either operational or connected) may be damaged in the process.

Recreating LRO Events on a Laboratory Scale

On an actual distribution feeder, DG would typically interact with other generation present nearby, as well as a number of local loads. For the process of testing the inverter's behavior to LRO events, the laboratory setup reduces the setup to a single inverter and a single local load. The local load can be scaled up or down, depending on the portion of the inverter's loading that is considered removed by the protective device operation. The remaining current flow (not flowing into the local load pre-disturbance) is absorbed by either a bidirectional grid simulator, or the combination of a unidirectional simulator and a ballast load.

The differences between the actual case and the recreated laboratory experiment are numerous:

1. Uses a single inverter as a proxy for multiple inverters, each with their own control loop.
2. Doesn't show the impact of composite loads (Constant resistance, constant power, etc) on the LRO event.
3. Doesn't reflect the impact of feeder or transformer impedances on the overvoltage.
4. Doesn't consider the impact of different breaker or fuse types on the overvoltage response.

However, as the tests are intended to determine the inverter's contribution to overall LRO events, it's important to keep these limitations in mind

Test Setup

The test configuration is shown in the block diagram below (Figure 2-1). The inverter's dc input is provided by the PV simulator, which emulates the current-voltage curve of an array. The inverter's output is connected directly to a wye-connected, three-phase load at a constant resistance. The output is then connected to a 3-pole breaker, with the AC supply and ballast load (to prevent the inverter backfeeding a unidirectional source) on the other side.

The data recorder monitors the voltages at the three-phase load, as well as the injected currents from the PV inverter. It also monitors dc voltage as an indicator for the operating state of the inverter (generating vs. tripped off-line). The voltage and current monitoring points are physically close to both the inverter and load, neglecting the potential impact of lengths of utility or customer wiring that would be present in an actual installation.

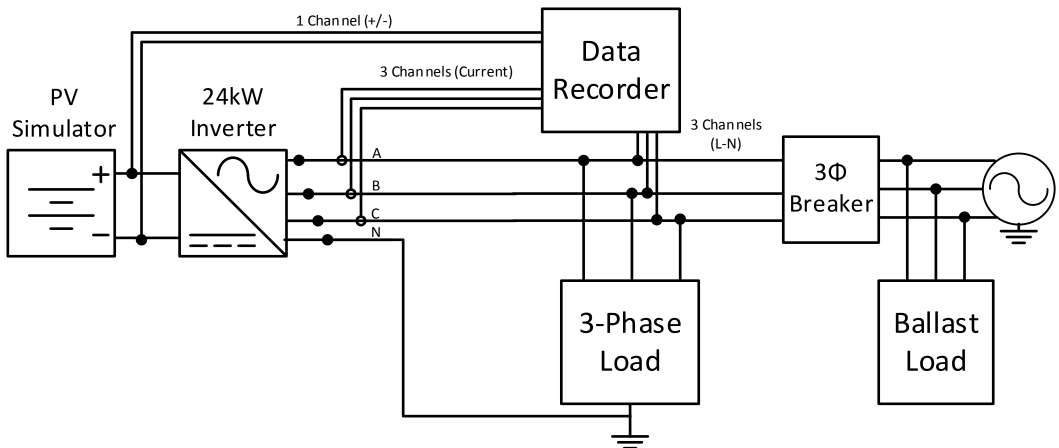

Figure 2-1
LRO Test Setup

Procedure

The test procedure for LRO is simple, and involves the following steps:

1. Set 3-phase load to the appropriate load level
2. Close 3-pole breaker
3. Energize AC supply to create voltage at the inverter terminals
4. Energize PV simulator outputs with appropriate current-voltage curve
5. Wait for inverter to begin exporting power and maintain a dc-operating point near (+/-3%) to the emulated maximum power point (MPP)
6. Open the 3-pole breaker and record data until the inverter ceases to energize the 3-phase load

The test is then repeat five times for each combination of inverter output power (50% or 100% of rating) and three-phase load. Repeating the same test multiple times reduces the impact of variations of point-on-wave (when the breaker opens) and the inverter's individual control variables.

Results

Because LRO is considered a "worst-case" event, the waveforms in the figures below indicate the worst (meaning highest overvoltage) cases that were observed during testing at each combination of inverter output and load. Figure 2-2 shows the resulting voltages observed at the 3-phase load, for the minimum combination of inverter output and load tested (12kW inverter output with 1kW load). This would reflect a generation to load ratio of 12-to-1, or 1200% of local load.

Prior to the breaker opening (time values less than 0.046 seconds), the grid simulator controls the load voltage to its rated value, and the ballast load consumes 11kW from the inverter output. Once the breaker opens at 0.046 seconds, the inverter quickly drives one of the phase voltages (Phase B) up to 1.6 per-unit. Once that value is reached, the inverter's internal protection quickly ceases operation. The residual load on the inverter-side of the contactor quickly drains the filter capacitors for the remaining observed interval. Though the voltage after the breaker opens is highly irregular, the inverter's protection scheme operates quickly enough to control the overvoltage.

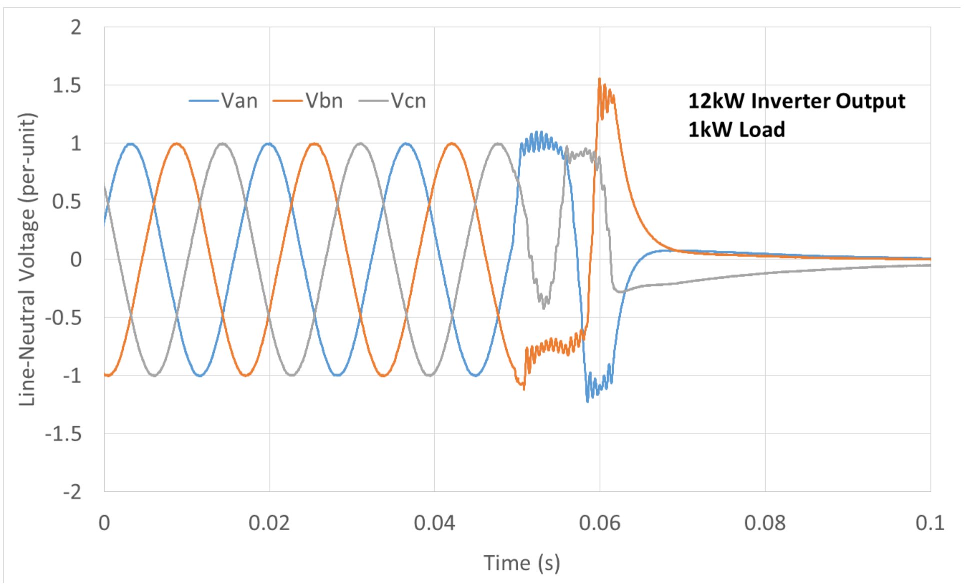

Figure 2-2
Inverter Terminal Voltages during LRO Test (12kW Output – 1kW Load)

With the inverter output increased to 100% of its rating (or 24kW), and the same generation to load ratio (12-to-1), Figure 2-3 shows the resulting voltage response at the load terminals. Due to the point on which the breaker opens, and the inverter's internal control states, Phase C is the voltage which quickly rises to roughly 1.4 per-unit, a slight reduction in the previous case. Though the generation to load ratio is similar, the increased residual load (2kW) compared to the same inverter passive filtering results in a peak voltage that is lower than the previous case (12kW output) with a faster rate-of-decay of the output voltage.

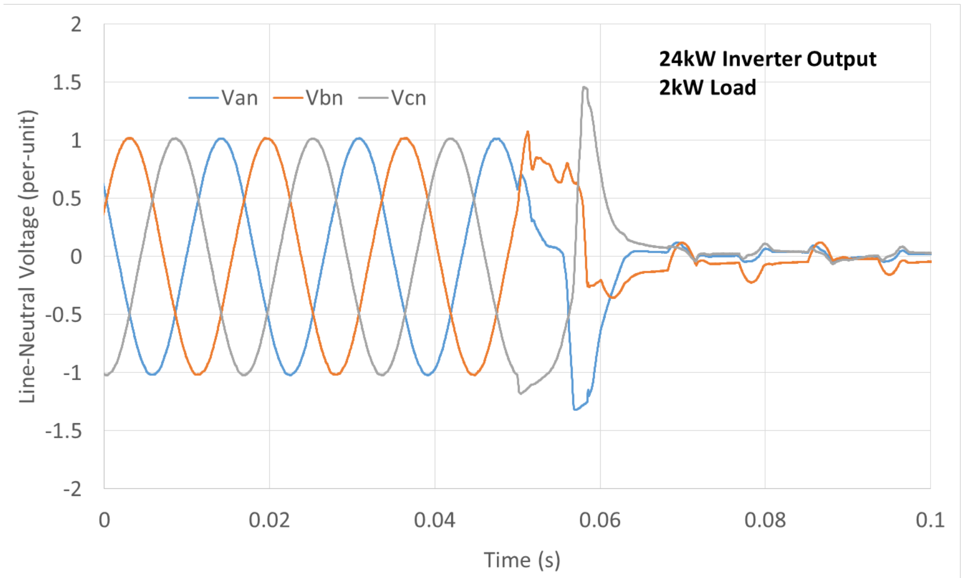

Figure 2-3
Inverter Terminal Voltages during LRO Test (24kW Output – 2kW Load)

Conversely, if the load power is increased up to a value equal to that of the inverter's output, Figure 2-4 and Figure 2-5 show the resulting voltage waveforms. After the breaker is opened (around 0.021 seconds in Figure 2-4), the inverter continues operation for several cycles. While the waveform is quite distorted, the overvoltage is much less severe in magnitude than the previous cases. The inverter continues to supply current to the 3-phase load until either the overvoltage limit is reach, or the anti-islanding protection is activated.

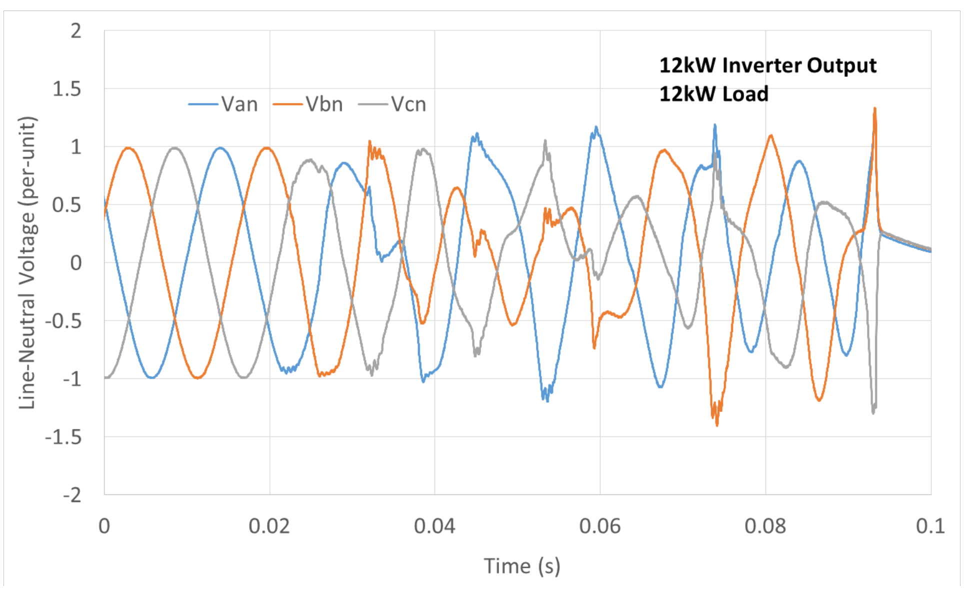

Figure 2-4
Inverter Terminal Voltages during LRO Test (12kW Output – 12kW Load)

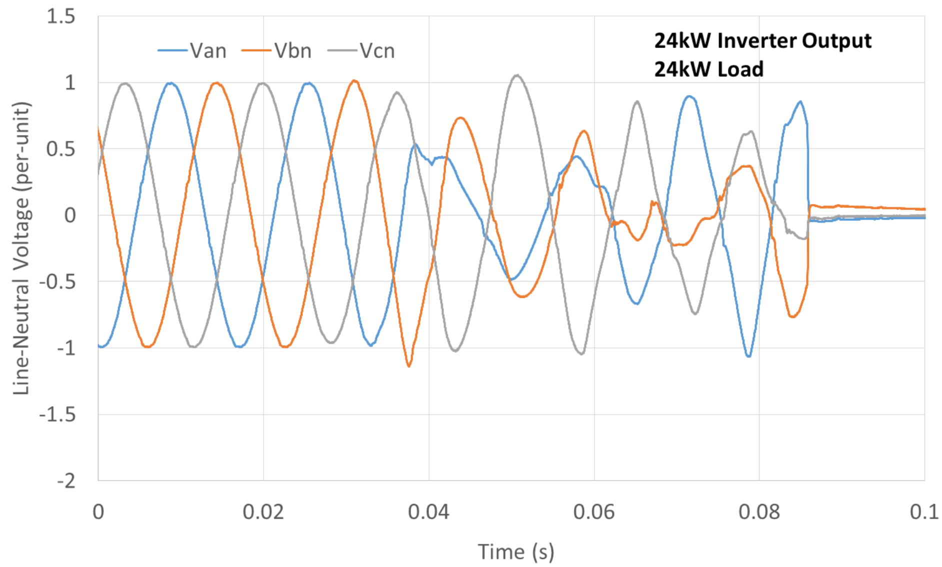

Figure 2-5
Inverter Terminal Voltages during LRO Test (24kW Output – 24kW Load)

With the load roughly equal to the inverter's output power, the expectation would be that the resulting voltage would be less distorted than the results shown in Figure 2-4 and Figure 2-5. A plot of the instantaneous output power in these two cases is shown in Figure 2-6. In both cases the inverter output power is not well regulated by the normal control loop. In this case, the limiting elements are the instantaneous or RMS overvoltage limits, as well as the anti-islanding protection.

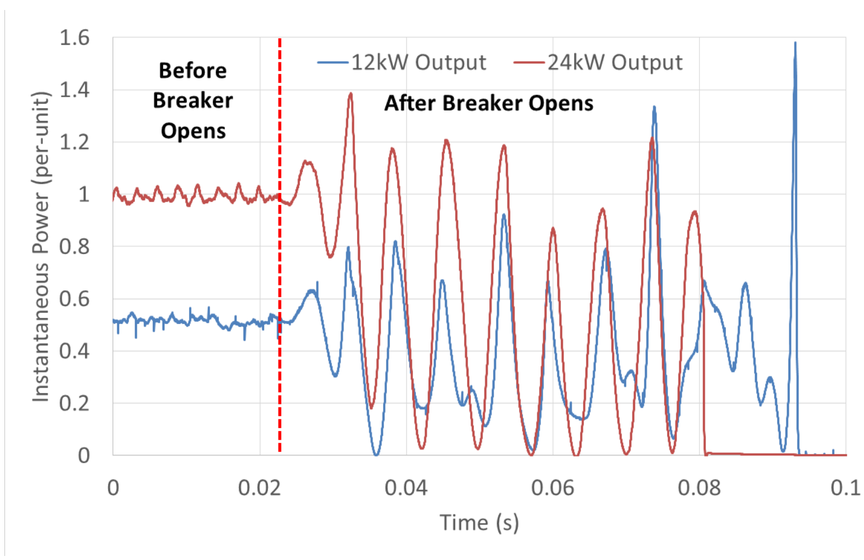

Figure 2-6
Instantaneous Output Power Before and After the Breaker Opens, and Load Equal to Inverter Output

Though the typical control loop is ineffective (as implemented) at regulating power while the inverter is islanded, the short-duration limits appear to operate effectively. A comparison of the inverter's responses at full output (24kW) but with 2kW and 24kW local load is shown in Figure

2-7. With only 2kW residual load left after the breaker opens, the overvoltage limits engage much more quickly than the 24kW case, ceasing the inverter's output.

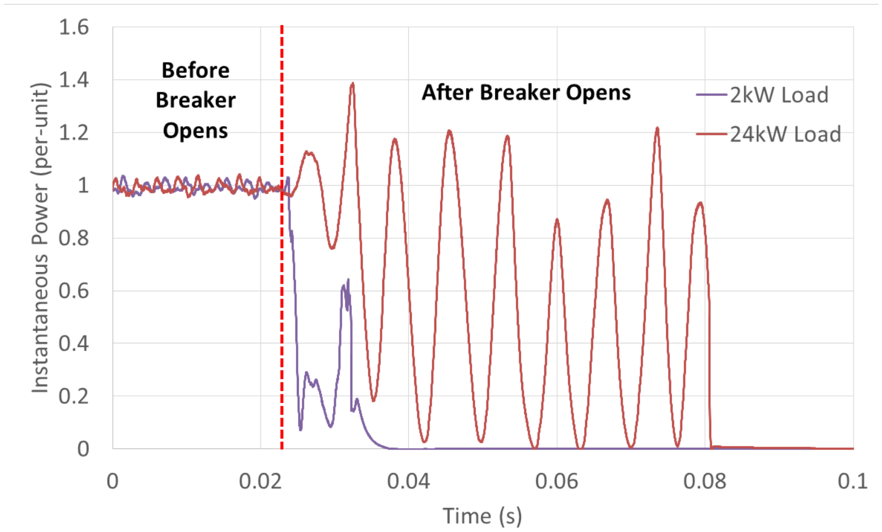

Figure 2-7
Instantaneous Output Power Before and After the Breaker Opens, and 2kW and 24kW Loads

Each of the five tests were repeated at individual load conditions that are shown in Table 2-1. The resulting maximum voltages are recorded in Figure 2-8 and Figure 2-9. Once again, depending on the point in the waveform cycle that the breaker is opened, and the inverter's internal control algorithm, any one of the three phases may record the highest voltage. In all cases, the inverter ceased operation within 3-4 cycles.

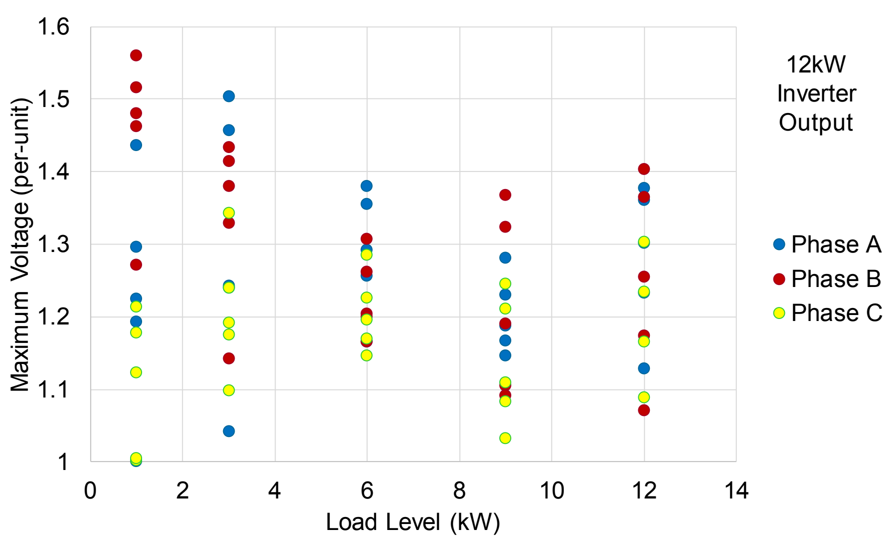

Figure 2-8
Maximum Recorded Voltages during LRO Test (In Per-unit) with 50% Inverter Output

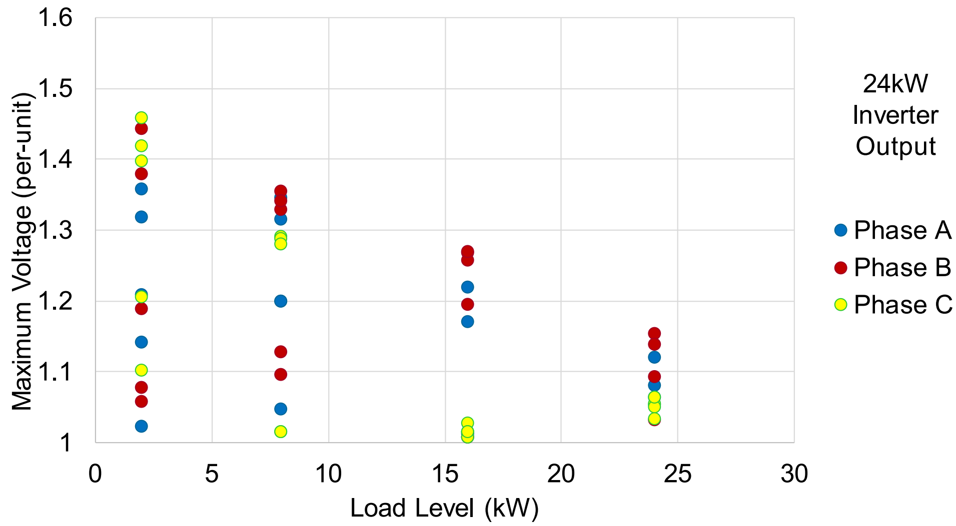

Figure 2-9
Maximum Recorded Voltages during LRO Test (In Per-unit) with 100% Inverter Output

Table 2-1
Tested Inverter and Load Configurations for LRO

Inverter Output	Load Power				
12kW	1kW	3kW	6kW	9kW	12kW
24kW	2kW	8kW	16kW	24kW	

For the purposes of potential damage to loads, the critical metric is not only the maximum voltage observed, but also the length of time these conditions are present. Because the area of concern is short-duration overvoltages (lasting a few milliseconds), the plots in Figure 2-10 and Figure 2-11 show the maximum consecutive time that the inverter output is above specified levels (1.1, 1.2, and 1.4 per-unit). No results were recorded above 1.6 per-unit. Because there is no standard acceptance criteria established for short-duration overvoltage, part of the ITIC[1] curve is indicated on the plot just to provide a frame of reference. As indicated, the vast majority of overvoltage events are very short-duration, and well within the tolerances of end user equipment. Only one outlier was observed to be above 1.2 per-unit for approximately 3.3ms. Similar to the maximum voltage recordings, the 24kW output cases show significantly less overvoltage duration than the 12kW outputs.

[1] Originally called "CBEMA" curve, from T. Key, IEEE Transactions on Industrial Applications, IA-15, No 4, pp 381-393, New York, Aug 1979, modified by Technical Committee 3 (TC3) of the Information Technology Industry Council in 1999 (ITI, formerly known as the Computer & Business Equipment Manufacturer's Association).

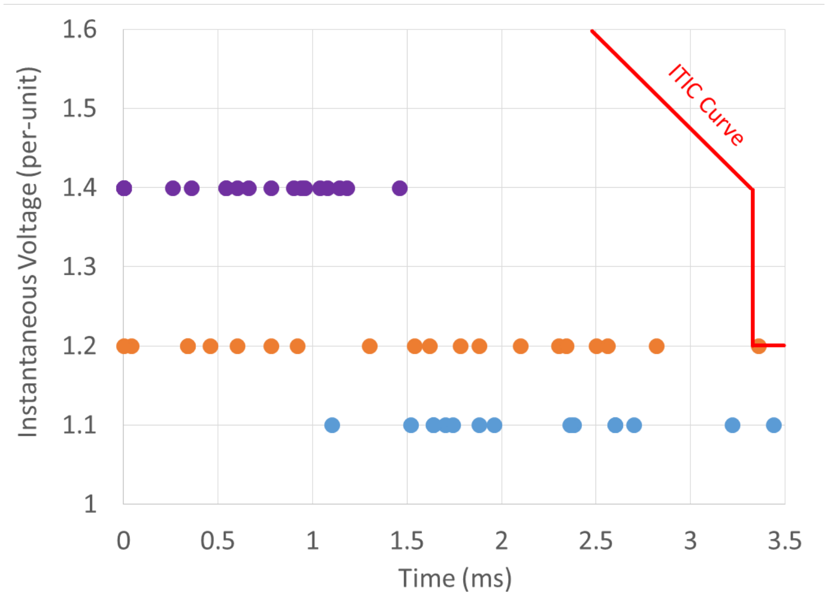

Figure 2-10
Recorded Consecutive Time above Key Voltage Levels during LRO Test (In Per-unit) with 50% Inverter Output

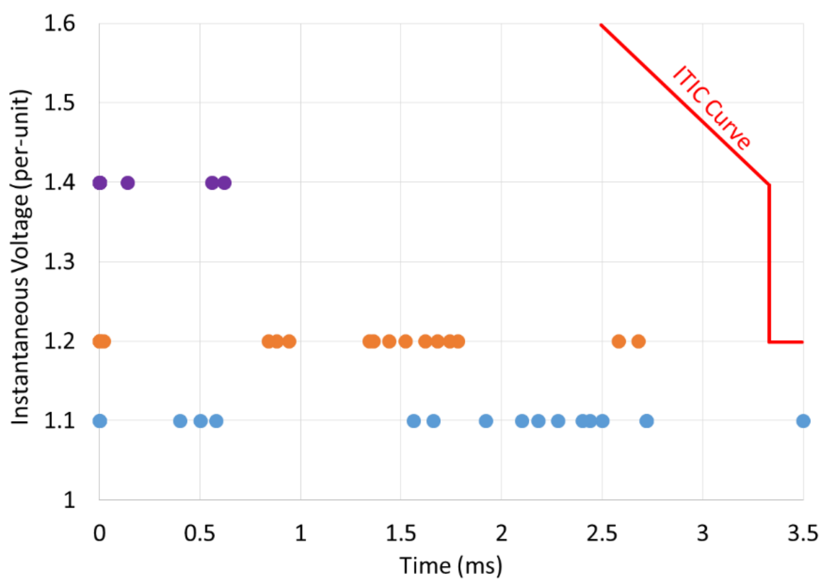

Figure 2-11
Recorded Time above Key Voltage Levels during LRO Test (In Per-unit) with 100% Inverter Output

Discussion

The initial load rejection overvoltage testing of a selected three-phase inverter has shown built-in limiting by the inverter's internal protections for all of the measured cases. The particular responses at each inverter output and load condition varied from run to run. This was in part a response to the point-on-wave that the utility breaker contacts opened, as well as an unpredictable response of the inverter's primary control loops when removed from the "stiff" utility source. With variation in the levels, inverter short-duration voltage limits and anti-islanding protections appear to successfully limit the voltage from rising higher than 1.6 per-unit. The duration of the LRO was also limited to 3-4 cycles after the breaker opened. It's unclear at this time if the mechanics of the primary control loop are typical of many three-phase inverters or unique to this particular model.

The behavior is a function of the controller parameters and the design of the inverter's phase-locked-loop (PLL). Future testing could accomplish to things, 1) identify control parameter that will mitigate LRO and 2) confirm if other inverter designs and types demonstrate the same behavior.

3
GROUND FAULT OVERVOLTAGE (GFO)

Background

Ground fault overvoltage (GFO) is different mechanism than LRO, with different issues. For GFO the cause of overvoltage is a grounded conductor in a three phase power system that shift the neutral point for line to neutral connected equipment. For DG, most of the industry's experience has been with synchronous machines and based on rotating machine theory. Published text and discussions addressing how DG may interact with a utility ground fault can be found in [3], [4], [10]. These references identify the following sequence of events as the potential concern:

1. A single-line-to-ground (SLG) fault occurs somewhere on a distribution feeder, downstream of a feeder breaker or other protective device.
2. The breaker opens somewhere between 1-10 cycles, isolating the fault from the rest of the upstream system.
3. A distribution connected DG, downstream of the breaker, continues operating and providing line-to-line voltage to surrounding loads
4. Because one of the phases is connected to ground, a neutral "shift" occurs, which increases the line-to-neutral voltages on the two unfaulted phases up to the line-to-line voltage.
5. If the GFO condition exists for an extended period, utility equipment or loads connected from line-to-neutral may be damaged as a result.

In synchronous machines, the SLG fault response is generally governed by the physical parameters of the generator, the interconnection transformer, and the grounding method chosen. With a machine design that is fixed, the design parameters are the transformer design and grounding system. Proper selection of both items is a trade-off between the short-circuit contribution of the generator and the potential to create overvoltage condition [1]. The relationship between "effective grounding" [5] and overvoltage has been well documented, and won't be investigated here.

Inverters, however, differ from synchronous machines significantly on this issue:

1. Even if the inverter presents a neutral for connection, most inverters don't generate power from line to neutral. Most inverters have a "pseudo-neutral" that moves in potential every IGBT switching interval and cannot be directly grounded.
2. Because the primary control loop of the inverter is to produce a constant current, rather than a voltage, they do not (in theory) produce line-to-line voltage
3. As demonstrated in the LRO tests, the inverter's control algorithms and short-duration protections drive the overvoltage behavior much more significantly than physical parameters.

However, without a solid theoretical and experimental basis for ruling out inverter's ability to cause GFO, the concerns carried over from synchronous machines remain.

Recreating GFO on a Laboratory Scale

GFO is a much more complicated phenomenon to test than LRO. Rather than try and emulate an actual feeder, with millions of combinations and permutations that can affect the test (such as breaker operation, load conditions, sag depth, fault location, etc.) a laboratory test procedure needs to isolate the inverter's individual contribution to the GFO event.

Thus, the test condition is the inverter ending up running with line-to-neutral connected loads and a phase that is faulted to ground. In the actual system, this results from the fault occurring followed by the feeder breaker operating. However, in the laboratory, this condition is difficult to recreate without risking damage to equipment through repeated exposure to high fault currents. Also, there is significant variability in the timing between the fault occurring and the operating of the breaker, which could be anywhere from 1 cycle to 10 cycles or more.

Because the goal is to observe the inverter behavior once the breaker is opened (with the interim period being of much less interest) this test procedure utilized EPRI's Port-O-Sag to open the simulated utility interface, **then quickly** short one of the inverter's outputs to ground. This process takes approximately 9 microseconds to complete, leaving a very short momentary period where the inverter is islanded without the fault present. Because this period is very short, the inverter can be operated with its normal protective and anti-islanding schemes still active.

Another key point about the GFO test is that field conditions are rarely such that generation will be balanced with load. This creates a situation where a GFO event could be coupled with a corresponding LRO event, which further complicates the analysis of GFO behavior. By only performing GFO tests with residual load expressly equal to the inverter output, an attempt is made to isolate the GFO response from the natural LRO event.

Another proposed method has been the favorite of the ITFEG group, and involves using a tuneable RLC load bank to create a stable island before disconnecting the simulated utility interface. In some ways, this is a purer demonstration of the inverter's contribution to GFO, but it requires the disabling of the anti-islanding protection and the load and generation to be matched perfectly (both real and reactive power) before disconnecting.

As in the LRO tests, the impedances in the circuit aren't going to match those of the physical system. Also, the transformer construction could impact results (especially units that utilize a 3-leg or 5-leg core).

Test Setup

The majority of the test setup for GFO is quite similar to that of the LRO configuration discussed in Chapter 2. The three-pole breaker from the LRO tests is replaced by the EPRI Port-O-Sag unit, whose functionality was discussed in Chapter 1. Also, for some of the GFO tests, a three-phase transformer was connected between the inverter and the three-phase load, as shown in Figure 3-1. The PV simulator is utilized with the same current-voltage characteristics as the LRO test configuration. However, the 3-phase load power can be fixed to a value equal to the inverter's output power. In order to establish a baseline evaluation, the inverter was also tested without an interconnecting transformer at both full power and 50% output.

In most of the cases (Delta-Wye, and both no transformer cases) the ac supply was run at 480-V output. Because of limitations in availability of a 1:1 interface transformer for wye-wye configurations, the ac supply was operated at a lower voltage (280-V) with the transformer configuration boosting to 480-V. Looking at voltages on a per-unit basis, this should have limited impact on results.

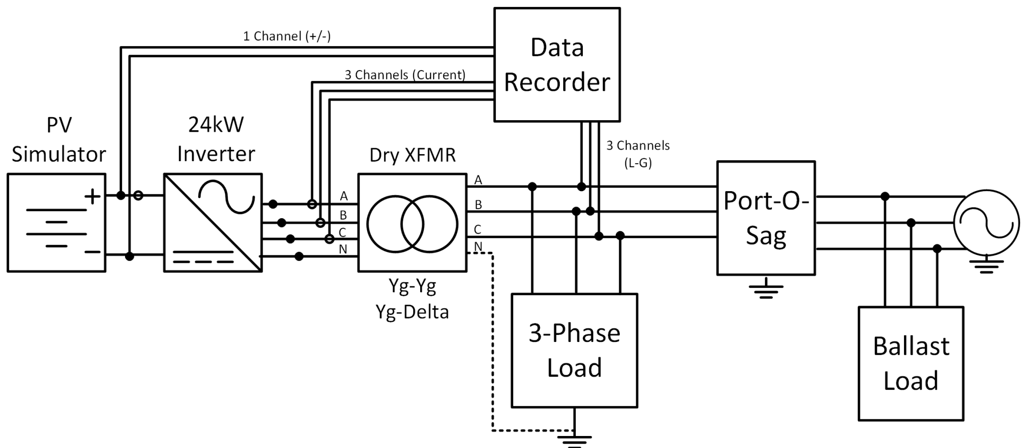

Figure 3-1
GFO Test Setup with an Interconnection Transformer

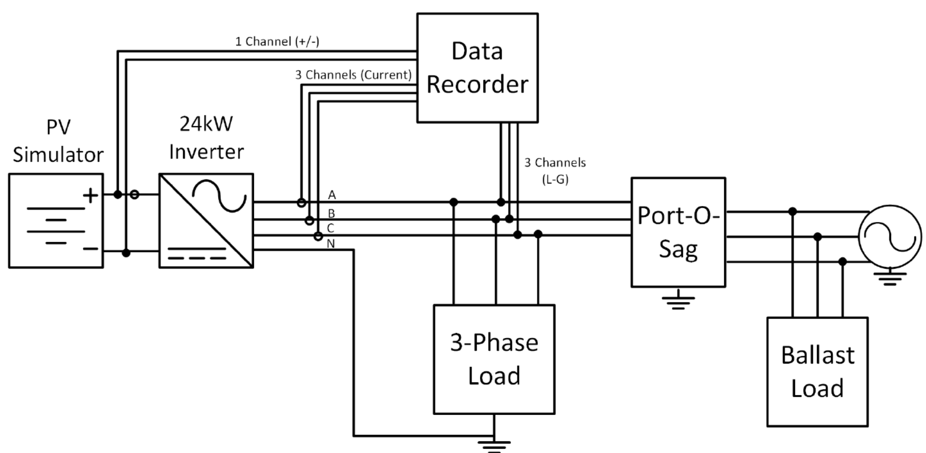

Figure 3-2
GFO Test Setup without the Interconnection Transformer

Procedure

1. Set 3-phase load to the appropriate load level
2. Connect the terminals of the Port-O-Sag by closing the internal contactor
3. Energize AC supply to create voltage at the inverter terminals
4. Energize PV simulator outputs with appropriate current-voltage curve
5. Wait for inverter to begin exporting power and maintain a dc-operating point near (+/-3%) to the emulated maximum power point (MPP)

6. Trigger the Port-O-Sag unit, which internally opens the interface contactor and closes the "fault" on the inverter side by grounding the C-phase of the inverters output to ground through an IGBT
7. Continue recording data until the inverter ceases operation

Results

As with the LRO tests in Chapter 2, each test condition was repeated five times with each test condition, to lessen the potential impact of the point-on-wave at which the Port-O-Sag would disconnect the utility. As a baseline, Figure 3-3 shows the GFO response of the inverter without an interface transformer. At roughly 0.053 seconds, phase C is faulted to ground through the Port-O-Sag's IGBT. The resulting voltage on the other two phases is slightly elevated (1.2 per-unit) until the inverter trips in 2 cycles. Two other points of interest in the waveform:

1. When the fault is applied from phase C to ground, there is a corresponding voltage spike on phase B. This is consistent with a rapid discharge of the filter capacitor on the C phase.
2. Once the inverter is disconnected from the utility, the voltage phase angle on the remaining phases quickly shifts to 180 degrees out-of-phase. This effect may not be consequential, since it only lasts for 1-2 cycles before the inverter ceases operation.

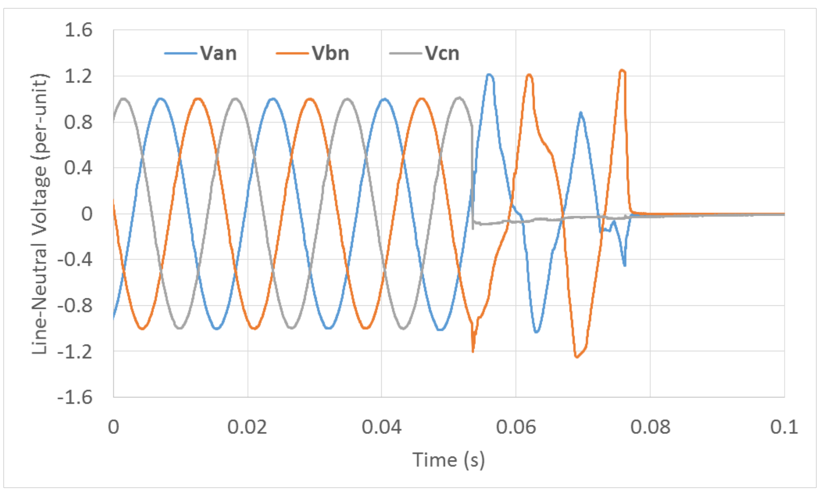

Figure 3-3
GFO Response without an Interface Transformer (50% Inverter Output)

There is a similar type of observed response with the wye-wye interface transformer, as the overvoltage is fairly consistent at 1.2 per-unit, up until the point that the controller's reaction to being islanded drives the per-unit voltage up (similar to the LRO events in the previous chapter)

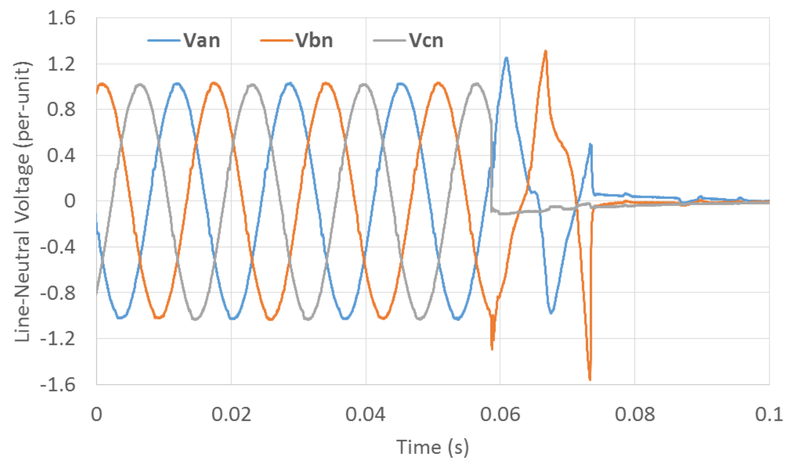

Figure 3-4
GFO Response with a Wye-Wye Interface Transformer (50% Inverter Output)

The imbalance and potential for GFO issues occur with the delta-wye configuration, shown in Figure 3-5. However, these are likely due to the transformer configuration itself, which has a known potential to cause GFO [1], rather than the inverter's inherent behavior.

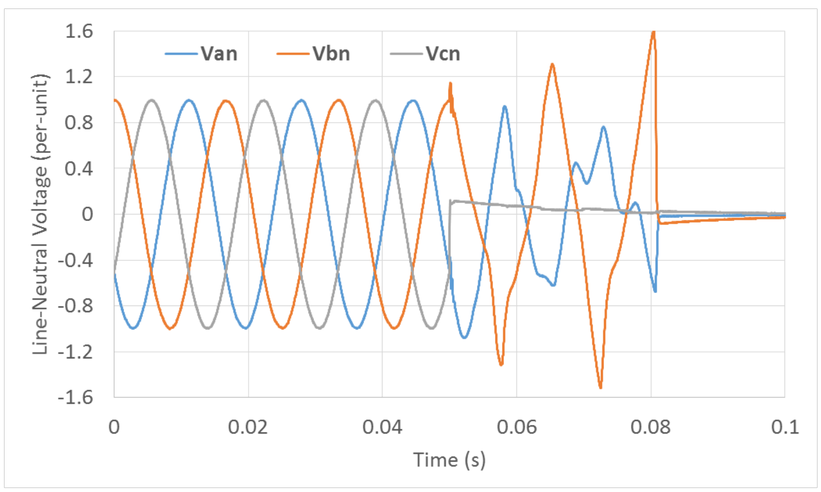

Figure 3-5
GFO Response with a Delta-Wye Interface Transformer (50% Inverter Output)

In all of the observed cases, the inverter under test's short-duration voltage limitations appear to function correctly, though the voltage may climb temporarily up to 1.6 per-unit. The observed voltage deviations do not specifically indicate GFO according to the traditional understanding, and are difficult to separate from the behaviors observed during LRO testing.

The test results for each of the runs are summarized by the maximum voltage and consecutive time above tables in Figure 3-6 and Figure 3-7.

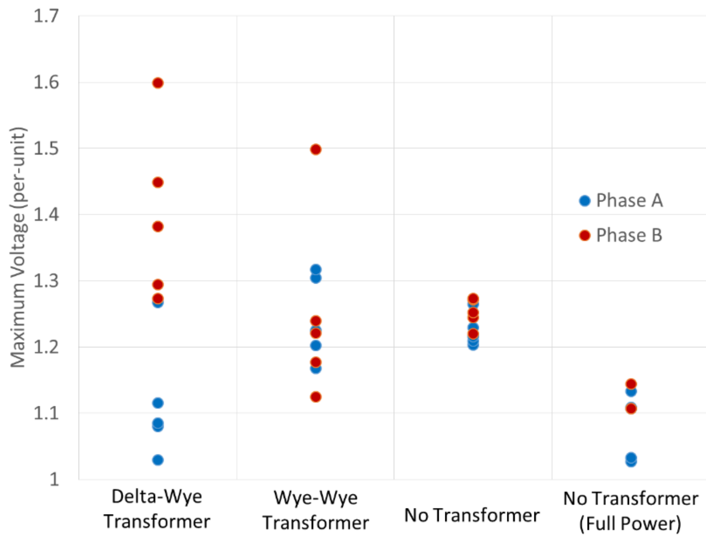

Figure 3-6
Maximum Recorded Voltages during GFO Tests

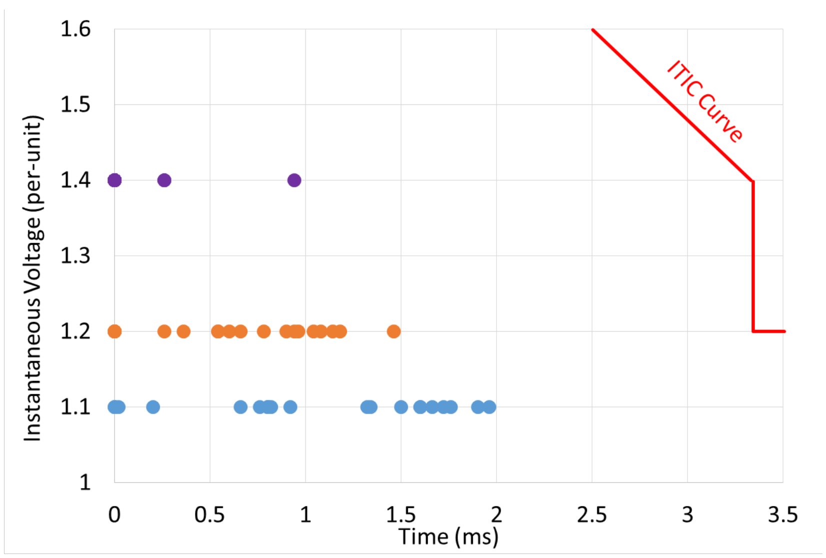

Figure 3-7
Consecutive Time above Key Voltage Levels Recorded during GFO Tests

Discussion

Based on the 24kW three-phase inverter testes, and the available testing equipment, the inverter does not contribute significantly to GFO. The testing did show unpredictability in the inverter control behavior. This was a similar finding to the inverter response in the LRO testing. The voltage at the output of the inverter was bounded at a level of 1.6 per-unit, even with a transformer configuration known to present GFO issues on certain systems (the delta-wye configuration). As in the LRO testing, additional sample should be looked at and the uncertainty around the control response investigated.

4 CONCLUSION

A key result of this work is that the new test procedures worked in the laboratory. Both the LRO and GRO procedures allowed evaluation of the inverter behavior in conditions reasonably similar to the anticipated field environment. It also provided insight into individual inverter's behavior and point out areas where additional investigation was needed.

Beyond proving out the new test procedures the results to date are limited based on the number of samples. For the limited samples results did show cases where overvoltage concerns are mitigated and not an issue. There are several areas of uncertainty and need for some additional work to fully understand how inverters respond and there contribution to overvoltage events. One area is the short-term dynamic behavior where inverter controls were found to be unpredictable and not well characterized. Another area of uncertainty is end-use load immunity in short duration time frames. There has been very little work in this area in the last 15 years, while the nature of end use load had been evolving especially in the area of lighting. Further work in all these areas may contribute to new interconnection standard specially related to inverter-based DG.

Also important to note is the current absence of acceptance criteria for inverter overvoltage in either LRO or GFO. Industry trade-groups, such as ITFEG, are currently working on compliance testing procedures in a collaborative space, but still lack the ultimate standard to which those results will be compared. In lieu of a true "damage curve" for consumer equipment, often the ITIC curve is used as a proxy. This is, by most accounts, considered a highly conservative estimate of the overvoltage tolerance of consumer equipment, and should be considered only a design guideline for those pieces of sensitive equipment and not a requirement for utility systems or other generation sources.

Related Efforts

Directly related to the testing efforts contained in this report is an effort in the Distribution program to translate these testing results into a useable model for system protection studies. This requires translating a short-duration behavior into a frequency domain model. As more tests are conducted at EPRI and in collaboration with other organizations, it should be possible to create a reasonable approximation for these systems in available software tools.

Though the test procedure used in this report is a variant of those being discussed with the Industry Task Force on Effective Grounding (ITFEG), their procedure is not yet completed. It will benefit from testing data that evaluates the effectiveness of existing procedures that can isolate LRO and GFO behaviors. The discussions would also benefit from understanding the rationale and results from alternative methods for testing inverter LRO and GFO.

Also related to this effort is an independent laboratory testing of both LRO and GFO at the National Renewable Energy Laboratory (NREL) in collaboration with SolarCity and Hawaiian Electric. EPRI is participating in the process as an advisor and reviewer of the test plan, results, and analysis. The effort focuses on primarily testing residential inverters (10kW or less) for

LRO, as well as some commercial units for GFO. By collaborating with NREL and other organizations, EPRI aims to leverage additional available funding and resources to create value for our members, providing insight into inverters and interconnection issues.

Summary of Future Work

As a follow on to the testing described in this report, the following are proposed as future work items:

- Continued testing with multiple types of faults (double-line-to-ground, phase-to-phase, etc)
- Analysis of inverter responses to different fault levels and impedances
- Testing of additional inverter models to establish a representative sample
- Testing of larger inverters common at utility-scale plants, which will require larger-scale testing equipment
- Further development of the test procedure to better isolate LRO and GFO behaviors

Though a reasonable expectation of the performance of the tested inverter may be ascertained by the test results in this report, it should not be considered exhaustive or necessarily representative of the inverter industry-at-large.

A
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3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com