Paper presented at the 36th IEEE Photovoltaic Specialists Conference, Seattle, WA (2011)

MULTI-PV INVERTER UTILITY INTERCONNECTION EVALUATIONS

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ABSTRACT

Utility-interconnected Photovoltaic (PV) systems are quickly becoming a mainstay in today's energy portfolio and will conceivably achieve a level of penetration where operation and performance of these devices is likely to influence the operation of area electric power systems (EPS). To achieve this, PV systems need to harvest all available energy from the solar resource, channel this energy and convert it to usable power, and provide a high level of performance and interoperability all while maintaining a level of confidence and reliability that fulfill the vested interest in PV technology. High penetration of PV systems is realized through two distinctly different approaches; a high number of small residential PV systems at a given locality, or the more influential approach of a centralized PV power station, where a multi-megawatt PV installation is comprised by numerous commercial-sized inverters. This report is focused on the interaction of multiple residential utility-interconnected PV systems connected to a single distribution transformer. Four residential inverters have been connected to a point of common coupling (PCC) along with a single RLC load that will absorb the real power and provide a resonant tank circuit tuned to 60 Hz to be used for evaluating loss of utility. Determination of the interoperability in a high penetration configuration will be evaluated in a laboratory setting at Sandia National Laboratories' Distributed Energy Technologies Laboratory. The evaluations will focus on power quality, start up/shutdown routines, utility compatibility, and loss of utility functions. The direct current (dc) source will be provided by a Programmable Photovoltaic simulator that is designed to provide dc power with settable irradiance and module temperature conditions. An alternating current (ac) utility simulator will provide the necessary anomalies on the ac line to investigate the responses of the inverters under test.

INTRODUCTION

As the implementation of PV systems continues to increase the technology's level of penetration on distribution circuits, concerns from the utility community have also increased and been fueled by events within the United States and from abroad. This concern is primarily focused on the high number of inverters connected to the utility at the PCC. An undesired island occurs when distributed generation sources and an associated load continue to operate outside the control of the utility.

Multiple inverters connected to the utility with minimal impedance between the distributed sources raises concerns about power quality, interoperability, and loss of utility detection in particular when the inverters are from different manufacturers utilizing different anti-islanding methods.

Large PV power plants typically utilize many inverters from the same manufacturer with the same type of anti-islanding method, which can cause *cancelling* effects if the anti-islanding method is an impedance measurement method and no synchronization is implemented. If a phase jump or active feedback type of anti-islanding scheme is used, the possibility of introducing power quality issues at the PCC on a large PV installation increases [1].

The focus of this paper is to investigate the high penetration of single phase residential PV inverters connected to 50kVA distribution transformer. Various configurations can be realized with this circuit. For this test setup, the small line impedances between the inverters are neglected and the RLC load is not distributed. Figure 1 below shows the test circuit for the multi-inverter performance evaluation.

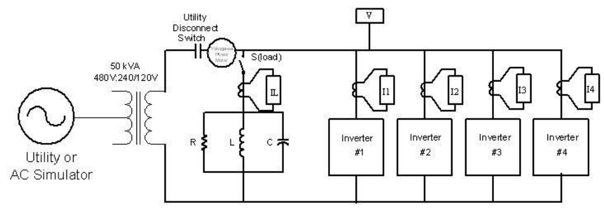

Figure 1. Multi-inverter test configuration

INVERTER PERFORMANCE VALIDATION TEST METHOLOGY

Utility-interconnected distributed generation devices are required to adhere to IEEE 1547-2003[2] utility interconnection standards for devices up to 10MVA. This standard provides the over/under voltage and frequency requirements, the voltage/frequency sag and surge response criteria, the power quality, and the loss of utility detection requirements for all distributed generation (DG) devices. The sequence for conducting anti-islanding evaluations on an inverter is to first determine the inverters' voltage and frequency operating ranges, which are the inverters' response time to the fast and slow disconnect times for voltage and frequency anomalies. The following are the suggested sequence of tests that the nationally recognized test laboratory (NRTL) certification process follows. The variation to this test procedure is evaluating multiple (four) inverters for each of the evaluations listed below.

Suggested Sequence

1. Response to abnormal voltage and frequency
2. Unintentional islanding

3. Harmonics

Response to abnormal voltage and frequency

The objective is to evaluate the passive anti-islanding protection function of the inverter under test and document the ability to detect the rms voltage or fundamental frequency. The inverters under test are nominally 240Vac split phase 60 Hz devices and the allowable operating voltage and frequency ranges are shown in table 1.

Table 1. O/U voltage and frequency values

Parameter under test	Standards Requirement On 240V_{ac} nominal
Low voltage disconnect	Vac < 211 (-12% of nominal)
High Voltage disconnect	Vac > 264 (+10% of nominal)
Low frequency disconnect	Frequency < 59.3
High Frequency disconnect	Frequency > 60.5

Voltage Range Results

These evaluations were conducted with the inverter operating at low power and are determined by programming a low irradiance condition into the PV simulator providing power to the four inverters under test. This minimizes the voltage regulation variation as the devices under test are disconnected from the simulated utility and the simulator has to pick up comparable load via the power generated by the inverters. Table 1 shows the values obtained during the evaluations and Figure 2 provides a sample test result.

Table 2. Low-voltage Range Results

Parameter under test Low voltage range	The inverters disconnected at this value (Vrms)
Inverter #1	215 Vrms
Inverter #2	213 Vrms
Inverter #3	215 Vrms
Inverter #4	214 Vrms

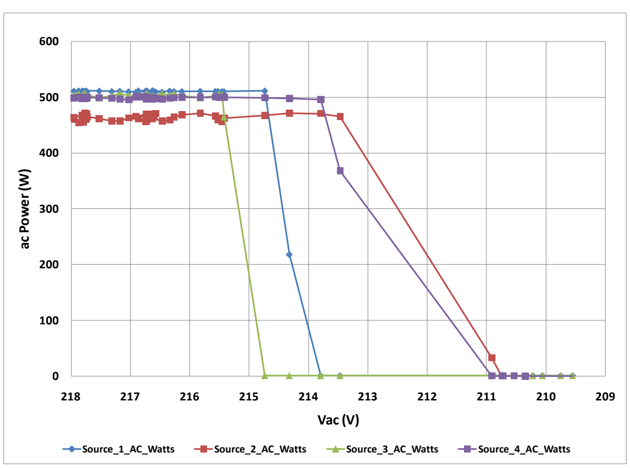

Figure 2. Low-voltage Range Results

The high-voltage range evaluation was accomplished by increasing the simulated ac line voltage until the inverters detected an out-of-compliance fault and ceased energizing the simulated grid. The plot below shows a significant power variation as the ac line voltage increases.

Table 3. High-voltage Range Results

Parameter under test High voltage range	The inverters disconnected at this value (Vrms)
Inverter #1	263 Vrms
Inverter #2	263 Vrms
Inverter #3	261 Vrms
Inverter #4	260-263Vrms (reduced power)

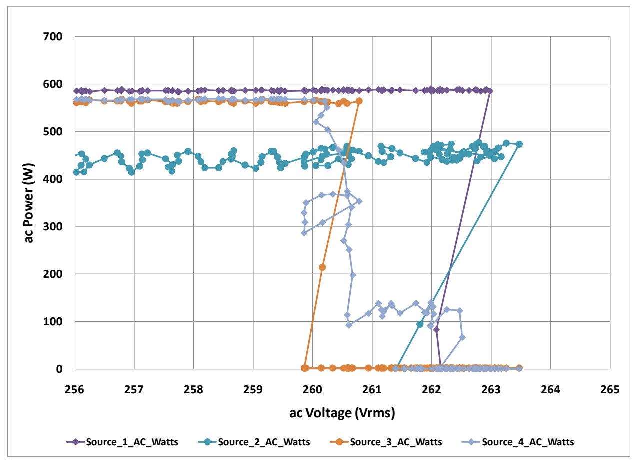

Figure 3. High-voltage Range Results

Frequency Range Results

Similar to the voltage range evaluations, this evaluation is conducted at low power levels and the frequency is varied slowly enough to capture sufficient data points to determine when the inverters reach out-of-tolerance conditions and cease energizing the simulated utility. Table 4 shows the static results for low and high frequency range tests and Figures 4 and 5 show a plot indicating the disconnect levels during the test.

Table 4. Low/High frequency Range Results

Parameter under test Low-frequency range	Inverters disconnected at this value (Hz)
Inverter #1	59.32 Hz
Inverter #2	59.4 Hz
Inverter #3	59.32 Hz
Inverter #4	59.32 Hz
Parameter under test High-frequency range	**Inverters disconnected at this value (Hz)**
Inverter #1	60.51
Inverter #2	60.41
Inverter #3	60.49
Inverter #4	60.49

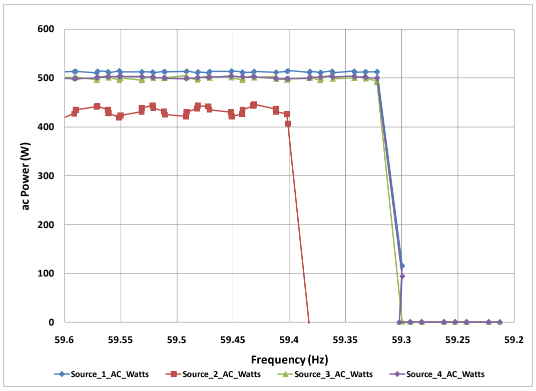

Figure 4. Low-frequency Range Results

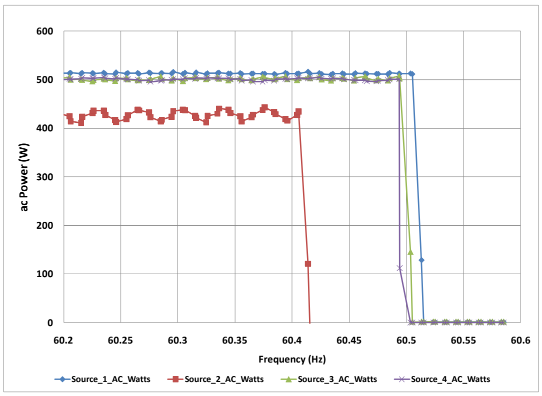

Figure 5. High-frequency Range Results

Voltage Surge and Sag Evaluations

After the static voltage and frequency ranges are determined, slow- and fast-response evaluations are conducted to analyze inverters' reaction to voltage and frequency anomalies that are slightly outside the predetermined static ranges. The purpose of these evaluations is to analyze the fast response of the inverter to voltage and frequency anomalies that are magnitude and duration in nature. Below is a table that shows the required response times according to the level of deviation from nominal ac voltage or frequency. Optimally, the response from each of the devices should be slightly within the maximum allowable response time, but the response varies considerably between manufacturers (Table 5). The response time of all three inverters can also be seen in the preceding three waveforms. The inverters do use a significant part of the allowable time during which they must respond, thus minimizing nuisance trips due to voltage variations. On the fast-response evaluation, two inverters do not respond within the allotted duration of 10 cycles.

Table 5. Voltage Surge and Sag Results

voltage range % of base voltage	clearing time (s)	Inv #1	Inv #2	Inv #3	Inv #4
V < 50	0.16	.13	>.16	.13	>.16
50 ≤ V<88	2.0	1.95	1.65	1.8	1.95
110 < V < 120	1.0	.017	.83	.81	.96
V ≥ 120	0.16	.017	.017	.017	.017

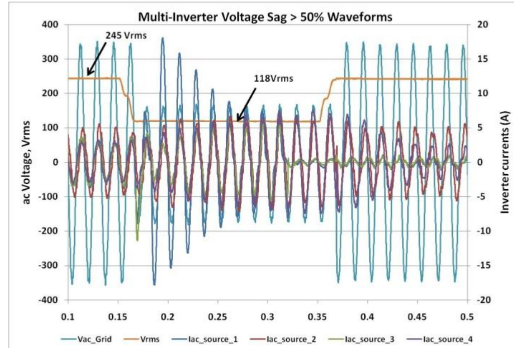

Figure 6. Voltage Sag Results for V< 50%

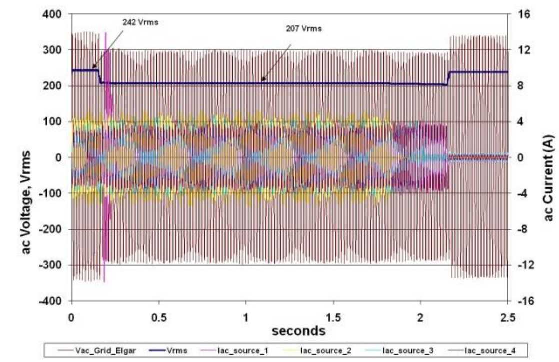

Figure 7. Voltage Sag Results for 50<V<88%

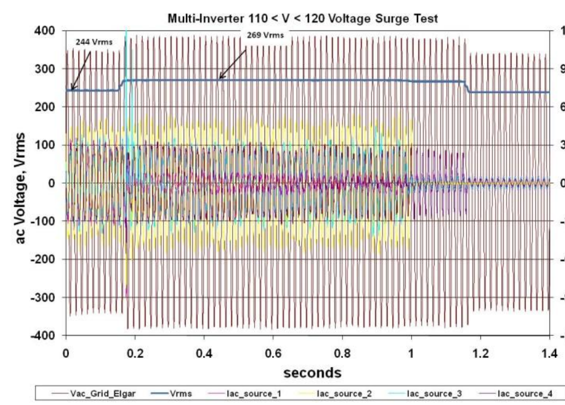

Figure 8. Voltage Surge 110<V<120%

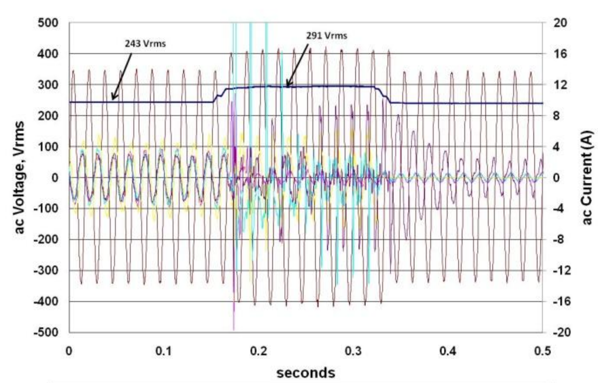

Figure 9. Voltage Surge V>120%

Table 6. Frequency Surge and Sag Evaluations

Frequency 60 Hz nominal	clearing time (s)	Inv #1	Inv #2	Inv #3	Inv #4
Freq < 59.3 Hz	0.16	0	.08	.08	,08
Freq > 60.5 Hz	0.16	.2	0	.12	.12

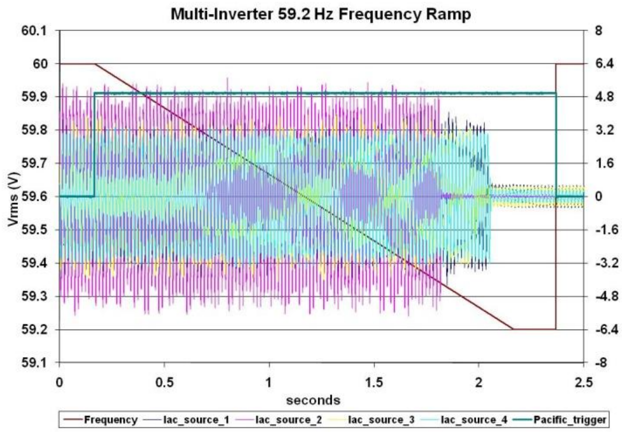

Figure 10. Frequency Sag Results

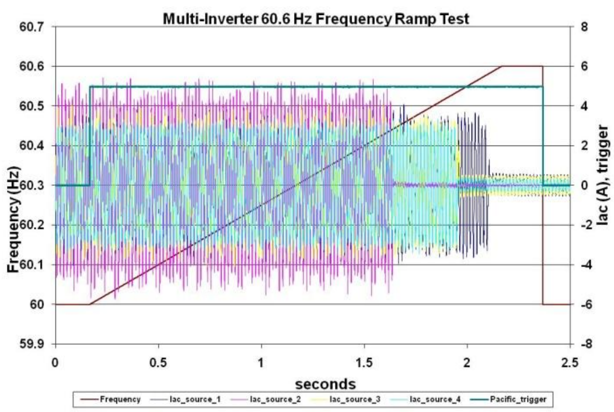

Figure 11. Frequency Surge Results

Power Quality Evaluations with Multiple Inverters

Utility-interconnected devices designed to energize the utility are required to deliver utility-grade power that is in accordance with IEEE 519[3]. When conducting evaluations for the certification process, the configuration requires only a single inverter in the testing circuit. This report implements a variation to normal evaluation procedures because the voltage and frequency tests presented have all been conducted utilizing the multiple inverter configuration. The power level of the inverters determines the electrical noise introduced by each of the inverters, which can make additional parameter measurements more difficult.

The total harmonic distortion (THD) measurements can be conducted utilizing either the area EPS voltage or an ac simulator's source voltage reference, which presents a cleaner source voltage and can lead to more favorable results. This testing configuration utilized the area's EPS source voltage during the THD evaluations. The evaluation's power levels utilized the same power levels described in the California Energy Commission's (CEC's) Inverter Performance Protocol [4]. These are the same power levels used when calculating the inverter's dc-to-ac conversion efficiency values. The following table lists the percentage of distortion the inverter's current may have at the given harmonic range. For harmonics within the specified range the individual harmonics must not pass the associated percentage.

Table 7. Harmonic Current of Distortion in % of Current

odd harms	h<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD
%	4	2	1.5	0.6	0.3	5

The evaluations were conducted at six power levels, so rather than presenting individual harmonic distortion ranges as shown in Table 7, the total demand distortion(TDD) will be presented at each of the power levels. This is done for the aggregate inverter current at the PCC.

Table 8. Total Demand Distortion (TDD) at the Six Power Levels

Power level	10%	20%	30%	50%	75%	100%
TDD %	22	13	9.7	7.2	4.9	4.1

The following plots show the current TDD at the different power levels for each of the inverters and the TDD for the total current at the PCC. Individual harmonic current values are also shown in the associated graphs. Figure 11 shows the results of the TDD evaluation at the PCC.

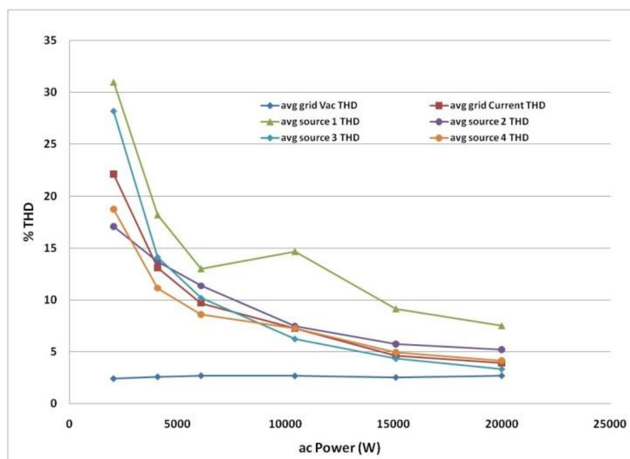

Figure 12. Multiple Inverter Power Quality Assessment

To show that the power quality is not influenced by the multiple inverter configuration on a single distribution transformer, the individual power quality assessments are presented below. From the data presented, it can be seen that inverter #2 operates marginally and inverter #1 is definitively outside the required TDD of 5% at rated power. Note that even with one out-of-compliance inverter and another that is marginal, the aggregate current is within the required 5% THD at rated power.

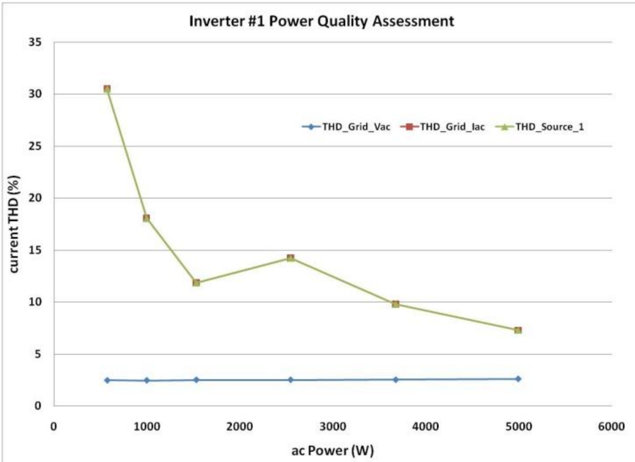

Figure 13. Inverter #1 Power Quality Assessment

The following plot shows an inverter that has a marginal power quality operation. Again providing the utility voltage source has a THD below 2.5% this assessment is valid.

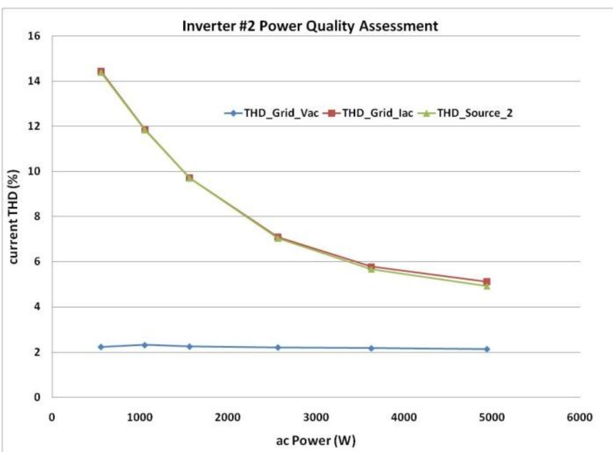

Figure 14. Inverter #2 Power Quality Assessment

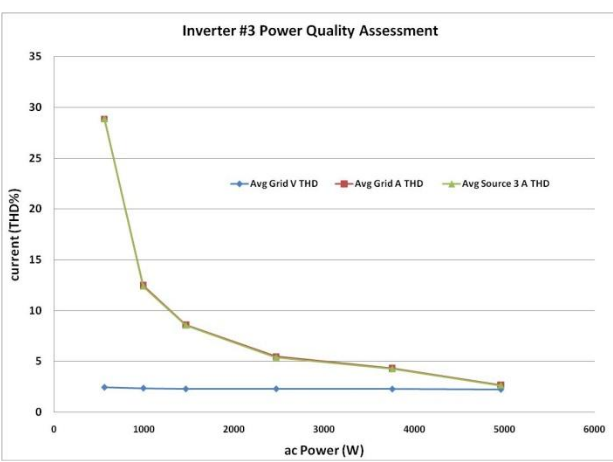

Figure 15. Inverter #3 Power Quality Assessment

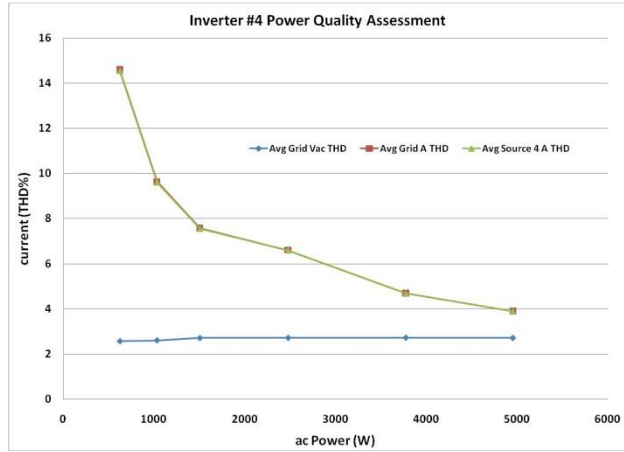

Figure 16. Inverter #4 Power Quality Assessment

LOSS OF UTILITY ASSESSMENTS

Underwriters Laboratories (UL) 1741[5] listed utility-interconnected PV inverters are certified individually. This has raised concern about cases in which PV inverters are interconnected onto the utility at a point where multiple inverters share the PCC, increasing the risk that different anti-islanding algorithms may have a cancelling effect on the certified algorithm. Likewise, a high number of inverters that rely on a synchronized method for the algorithm to be desensitized may have a loss of utility (anti-islanding) issue.

IEEE's 1547 interconnection standard requires the device under test to be evaluated at three different power levels, and for the tuned resonant circuit to be varied by ~ 1% for each of the 10 tests conducted at various power levels. These evaluations are conducted at 33%, 66%, and 100% of rated power. If the device under test responds within two seconds and ceases to energize the utility, then the inverter is recognized as **compliant** with utility interconnection standards. If ***any*** of the tests result in a response time that is longer than two seconds, then the inverter has failed the anti-islanding evaluations and further investigation is required.

Loss of Utility Testing

As noted in Figure 1, inverters in this test are operated at the required power level and the RLC circuit is adjusted to provide a quality factor (Q_f) of 1 and a real power-to-generated power match of 1. The Q_f is determined using the following equation:

$$Q = R\sqrt{\frac{C}{L}}$$

Where: the parameter describes the amount of stored energy to the energy dissipated in the RLC circuit. The higher the Q_f the more difficult for anti-islanding algorithms to detect the islanded circuit.
The multi-inverter islanding tests were conducted at three power levels and, at each power level, 10 islanding tests

were conducted. Table 9 shows the longest recorded islanding duration at each of the power levels.

Table 9. Islanding Duration at each Power Level

% of Inverter Power Level	Longest Measured Trip Time at Each Power Level
33% of rated power	.28 seconds
66% of rated power	.61 seconds
100% of rated power	.68 seconds

The following plots show the islanding waveforms at each of the three power levels. The waveforms show the source currents and a trigger signal transition that indicates when the utility was removed and during which the sources are energizing the islanded loads.

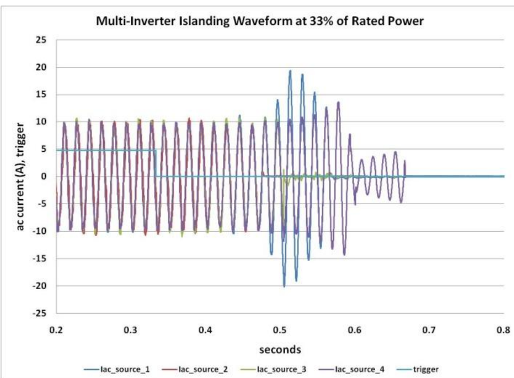

Figure 17. Islanding Waveform at 33% of Rated Power

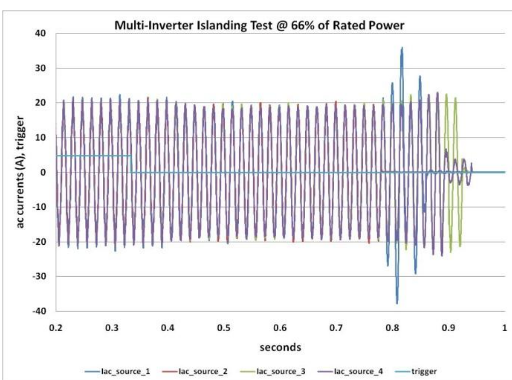

Figure 18. Islanding Waveform at 66% of Rated Power

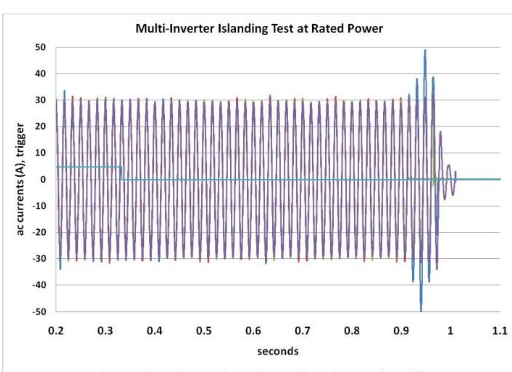

Figure 19. Islanding waveform at rated power

CONCLUSION

These multi-inverter utility interconnection evaluations have looked at utility compatibility assessments, voltage and frequency anomaly responses, power quality assessments, and the loss of utility detection capabilities as described in the utility interconnection standard. The evaluation connected multiple inverters certified to meet IEEE 1547 and investigated the interactions among the sources. This evaluation indicated the multi-inverter configuration did not interfere or cause the inverters to operate incorrectly.

Next Steps

Further investigation will involve characterizing each of the inverters and see if the multi-inverter configuration influences the anti-islanding characteristics. Future work will also investigate the multi-inverter case with the inverters operating in a smart-grid compatible mode, and will examine whether the inverters can remain compliant to interconnection standards.

ACKNOWLEDGEMENTS

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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