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PV Microinverter Testbed for Interoperability

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***Abstract* — This test plan is intended to provide verification for conformance of interconnection systems (ICSs) test criteria from IEEE Standard 1547-2005 [1], but applied to a testbed of several interconnected microinverters. These tests provide evaluation procedures for multi-manufacturer microinverter interoperability. The purpose of these procedures is to develop a standard method for evaluating interconnected microinverters. Utility compatibility evaluations determine the voltage and frequency operating ranges and the microinverter's response to a voltage/frequency sag or swell, and the response to an interruption in utility service.**

***Index Terms* — circuit testing, distributed power generation, frequency response, IEEE standards, inverters, power conversion harmonics, power system interconnection.**

I. Introduction

Microinverter implementation in residential photovoltaic (PV) systems is increasing. This is due to the potential performance advantages and attributes inherent to the microinverter topology. These attributes include the mitigation of DC balance of system (BOS) requirements, reduction in the presence of high dc voltage, and the reduction of the impact that module mismatch and shading has on the power production of a PV system. While these attributes can have a significant positive impact, mass implementation can only be possible if sufficient interoperability of interconnected microinverters can be achieved.

IEEE 1547 [1] and UL 1741 [2] compliance is achieved through individual testing of devices. Microinverters are designed to connect to one, or sometimes two, individual PV modules, and therefore will be highly likely to be interconnected with many others in a PV array. Also, in a residential setting with more than one customer PV system connected to a service transformer, microinverters may be forced to function within short electrical distance from other microinverters of different manufacture. There is a concern for verifying listed microinverter compliance in such settings.

This test plan is intended to provide verification for conformance of interconnection systems (ICSs) test criteria from IEEE Standard 1547-2005 [1], but applied to a testbed of several interconnected microinverters. These tests also provide evaluation procedures for multi-manufacturer microinverter interoperability. The purposes of these procedures are to:

1) Develop a standard method for evaluating interoperability of multiple interconnected microinverters

2) Identify any areas where future development may enhance inverter capabilities and performance.

Utility compatibility evaluations determine the voltage and frequency operating ranges, the inverter's response to a voltage/frequency sag or swell, and the response to an interruption in utility service. Test criteria are specified in UL 1741 [2] and IEEE 1547-2005 [1].

II. Test Configuration

The tests were performed using PV power from a testbed of 21 monocrystalline, 60 cell modules. The modules are arranged in three horizontal rows of seven modules in landscape orientation, mounted on a fixed, latitude-tilt rack (35°). The modules are rated at 245 Wp at STC, resulting in three rows of approximately 1.7 kW_{dc} each, or approximately 5.1 kW_{dc} total for the entire array.

Each module in a row is connected to a microinverter in a string of 7 paralleled, identical microinverters, with a different manufacturer of microinverter used on each string. Each of the three microinverter models chosen is compatible with the module characteristics, including input power range, maximum open-circuit voltage (V_{OC}), peak power tracking voltage, and maximum short circuit current (I_{SC}). Each microinverter model has a $240V_{AC}$ nominal output with a mix between models providing two $120V_{AC}$ lines referenced to neutral and a model providing a $240V_{AC}$ line-to-line output with no neutral. The three strings of microinverters under test are connected to a point of common coupling (PCC) on the secondary side of the service transformer, as three residential systems might be in the field, but with much greater electrical proximity in this case. A one-line diagram of the testbed configuration is shown in Fig. 1.

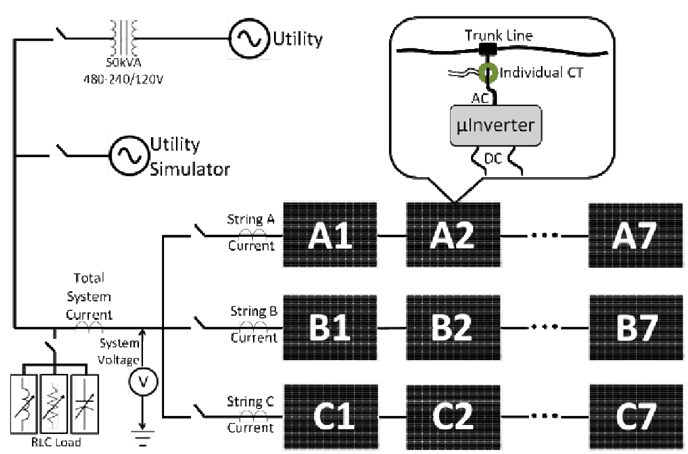

Fig. 1. Microinverter testbed configuration diagram.

The testbed was set up with the ability to disconnect each string individually for different configurations. The utility and transformer can be switched in and out with an AC disconnect for normal operation and anti-islanding tests. The Utility Simulator can be connected in lieu of the utility for grid compatibility tests. The Utility Simulator has regenerative capability for the testbed power output. Configurable resistive (R), inductive (L), and reactive (C) loads can be interconnected for anti-islanding testing.

Instrumentation was installed, calibrated, and configured to collect the many parameters needed for test results. Wide-band, 50A rated current transducers (CTs) were installed on one leg of each microinverter to monitor individual AC current outputs and harmonics. No DC instrumentation was installed. CTs were also installed to monitor each string and total system level current and harmonics. A single system voltage probe was installed at the PCC to monitor system voltage, frequency, and harmonics pertaining to the entire paralleled system. Other instrumentation was installed, including irradiance measurements, ambient temperature, module temperatures, and trigger signals from the simulator and utility AC disconnect.

III. Test Plan

Virtually all modern grid-tied PV microinverters use an algorithm to extract the maximum power available from the PV module(s) in response to variable conditions (e.g. varying irradiance and temperature). Without disabling this feature it is generally not straightforward either to request specific power levels from the inverter or to operate the inverter at specific voltage levels. The approach taken will be to evaluate a number of parameters by operating the inverter with a PV module configured to provide as close to maximum rated inverter power as possible. It is recognized that different results may be obtained using modules with different maximum-power-point voltages and currents, but these differences are generally not significant. It is felt that this method maximizes the amount of useful data that can be obtained in a reasonable testing period.

These procedures specify selected type tests performed on a testbed of several different microinverters to demonstrate that the interconnection functions and equipment of the microinverters conform to IEEE Std 1547 [1] when interconnected. The tests have been modified to apply to the testing of several interconnected microinverters, with instrumentation to verify compliance as a system as well as each individual unit. Each test was repeated a minimum of 3 times. Due to the 21 individual sets of parameters collected, string level data were plotted in many cases for visual purposes. It is important to note that individual currents were also examined in all cases. In the waveform plots, the higher voltage levels plotted correspond to the RMS voltages described in each test procedure. The small residual current levels seen after the microinverters have stopped producing power are due to filtering elements within the devices.

The voltage and frequency magnitude and trip time tests were only performed on the entire system and not on each string individually, nor any pairs of strings. The data collection resolution for the magnitude tests was one data point per second. The data collection resolution for the trip time tests was six thousand data points per second.

A. Test for response to abnormal voltage conditions

The tests for response to abnormal voltage conditions are specified in IEEE Standard 1547-2005 [1], Section 5.2. This includes tests for over- and undervoltage. These tests will verify that the microinverter system units cease to energize the grid for over- and undervoltage conditions. The tests will determine the magnitude and trip time for each condition function. Each procedure is applied to the testbed as an interconnected system using the Utility Simulator.

Test for overvoltage – magnitude - The test for overvoltage magnitude was used to verify each microinverter's overvoltage operating point. A function was executed through the Utility Simulator to ramp the voltage up and verify the disconnect magnitude of each microinverter was at or below 110% (264V) of nominal voltage (240V) at the PCC, and repeated 4 times. The entire system was producing approximately 83.1% of system rated maximum AC real power prior to the start of the overvoltage function. Fig. 2 shows a plot of the individual microinverter real power outputs versus the increasing PCC voltage.

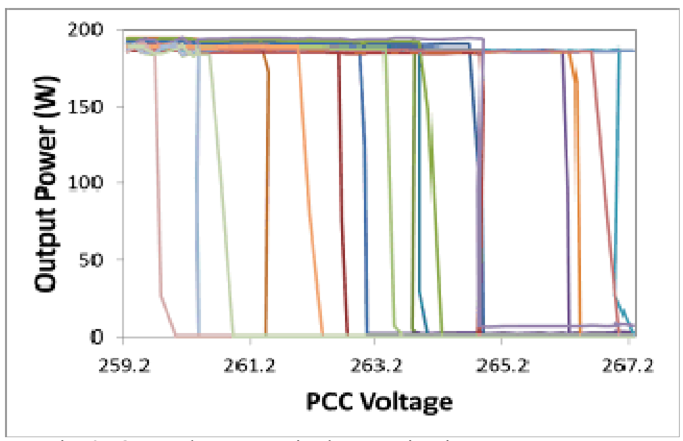

Fig. 2. Overvoltage magnitude test microinverter output powers.

As seen in Fig. 2, 8 of the 21 microinverters did not cease to produce power at or below the 264V/110% threshold. Each string had at least one violator in this configuration. These results were confirmed in the repeated tests.

Tests for overvoltage – trip time – The tests for overvoltage trip time were used to verify each microinverter's disconnect time for two different magnitudes of voltage surges. Two step functions were executed separately through the Utility Simulator to step the voltage up to slightly over both

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110%/264V and 120%/288V and verify the disconnect time of each microinverter was at or below the required 60cycles/1.00s and 10cycles/0.16s, respectively. Fig. 3 and Fig.4 show the respective waveform plots of the individual string currents and voltage for each overvoltage test.

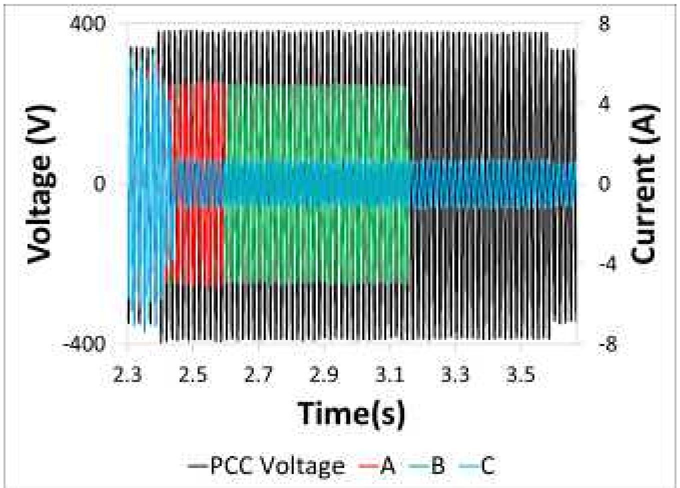

Fig. 3. 110% voltage step trip time test.

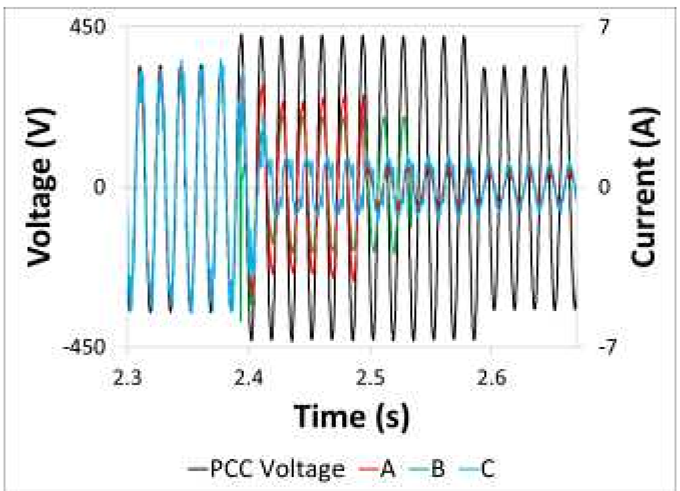

Fig. 4. 120% voltage step trip time test.

Fig. 3 and Fig. 4 show that all microinverters in the system overvoltage tests met the disconnect time requirements.

Test for undervoltage – magnitude - The test for undervoltage magnitude was used to verify each microinverter's undervoltage operating point. A function was executed through the Utility Simulator to ramp the voltage down and verify the disconnect magnitude of each microinverter was at or above 88% (211.2V) of nominal voltage (240V) at the PCC, and repeated 4 times. The entire system was producing approximately 83.5% of system rated maximum AC real power prior to the start of the undervoltage function. Fig. 5 shows a plot of the individual microinverter real power outputs versus the decreasing PCC voltage.

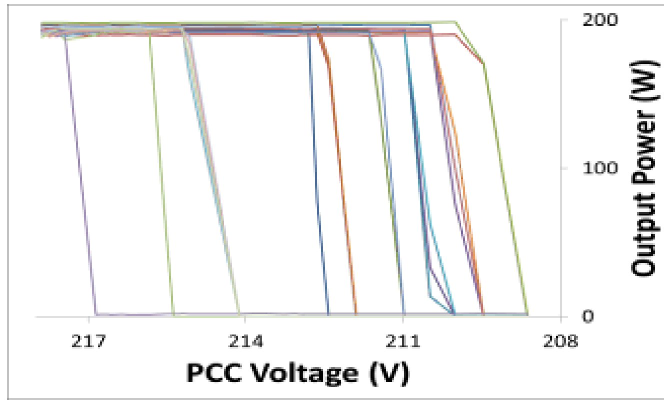

Fig. 5. Undervoltage magnitude test microinverter output powers.

As seen in Fig. 5, 9 of the 21 microinverters did not cease to produce power at or above the 211.2V/88% threshold. Two of the three strings had violators in this configuration. These results were confirmed in the repeated tests.

Tests for undervoltage – trip time – The tests for undervoltage trip time were used to verify each microinverter's disconnect time for two different magnitudes of voltage sags. Two step functions were executed separately through the Utility Simulator to step the voltage down to slightly below both 88%/211.2V and 50%/120V and verify the disconnect time of each microinverter was at or below the required 120cycles/2.00s and 10cycles/0.16s, respectively. Fig. 6 and Fig. 7 show the respective waveform plots of the individual string currents and voltage for each undervoltage test.

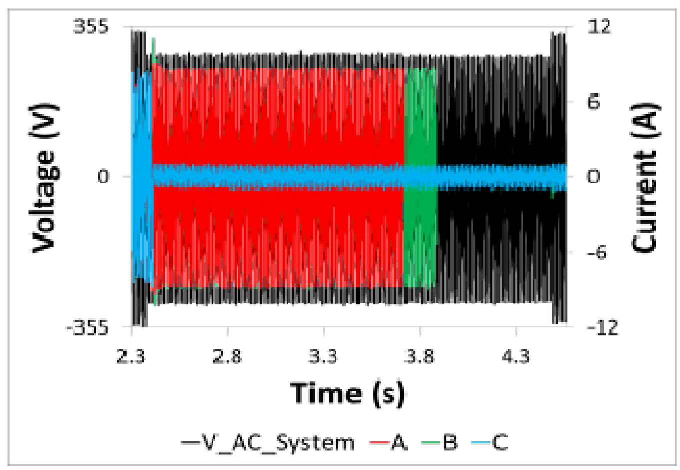

Fig. 6. 88% voltage step trip time test.

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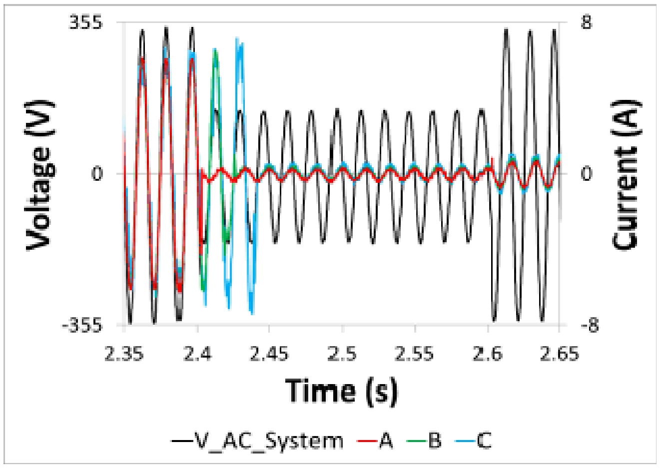

Fig. 7. 50% voltage step trip time test.

Fig. 6 and Fig. 7 show that all microinverters in the system undervoltage tests met the disconnect time requirements.

B. Response to abnormal frequency conditions

The tests for response to abnormal frequency conditions are specified in IEEE Standard 1547-2005 [1], Section 5.3. This includes tests for over- and underfrequency. These tests will verify that the microinverter system units cease to energize the grid for over- and underfrequency conditions. The tests will determine the magnitude and trip time for each condition function. Each procedure is applied to the testbed as an interconnected system using the Utility Simulator.

Test for overfrequency – magnitude - The test for overfrequency magnitude was used to verify each microinverter's overfrequency operating point. A function was executed through the Utility Simulator to ramp the frequency up and verify the disconnect magnitude of each microinverter was at or below 60.6Hz as measured on the PCC voltage. The entire system was producing approximately 78.4% of system rated maximum AC real power prior to the start of the overfrequency function. Fig. 8 shows a plot of the individual microinverter real power outputs versus the increasing PCC frequency.

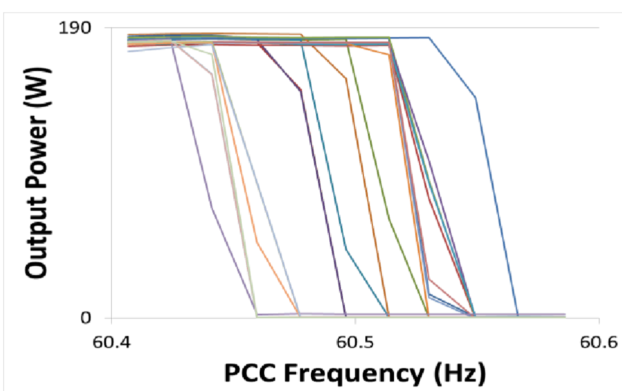

Fig. 8. Overfrequency magnitude test microinverter outputs.

As seen in Fig. 8, all of the microinverters disconnected below the 60.6Hz threshold.

Tests for overfrequency – trip time – The test for overfrequency trip time was used to verify each microinverter's disconnect time for a frequency surge. A step function was executed through the Utility Simulator to step the frequency up to 60.6Hz and verify the disconnect time of each microinverter was at or below the required 10cycles/0.16s. Fig. 9 shows the waveform plots of the individual string currents, with trigger signals indicating the start of each step, for the overfrequency test.

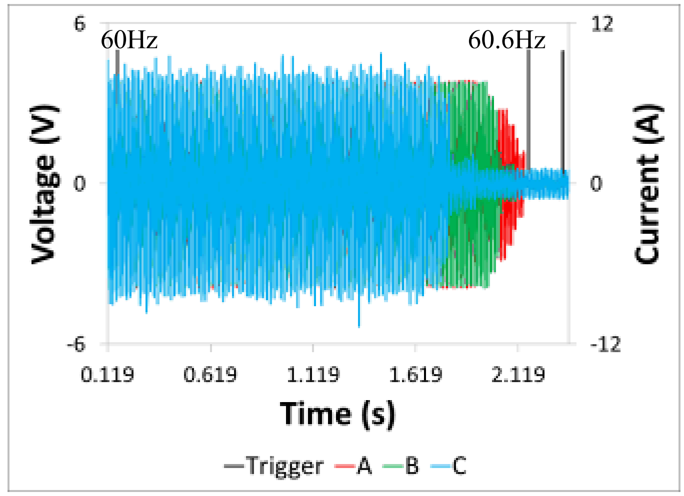

Fig. 9. 60.6Hz overfrequency trip time test.

In Fig. 9 the frequency was swept from 60Hz to 60.6Hz over two seconds and held there for 0.16 seconds (second to third trigger signals shown). Each string disconnected well before the frequency reached 60.6Hz.

Test for underfrequency – magnitude - The test for underfrequency magnitude was used to verify each microinverter's underfrequency operating point. A function was executed through the Utility Simulator to ramp the frequency down and verify the disconnect magnitude of each microinverter was at or above 59.2Hz as measured at the PCC voltage. The entire system was producing approximately 80.1% of system rated maximum AC real power prior to the start of the undervoltage function. Fig. 10 shows a plot of the individual microinverter real power outputs versus the decreasing PCC frequency.

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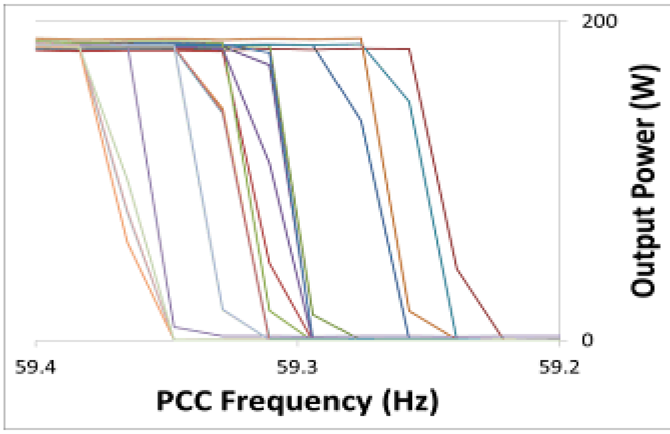

Fig. 10. Underfrequency magnitude test microinverter outputs.

As seen in Fig. 10, all of the microinverters disconnected above the 59.2Hz threshold.

Tests for underfrequency – trip time – The test for underfrequency trip time was used to verify each microinverter's disconnect time for a frequency sag. A step function was executed through the Utility Simulator to step the frequency down to 59.2Hz and verify the disconnect time of each microinverter was at or below the required 10cycles/0.16s. Fig. 11 shows the waveform plots of the individual string currents, with trigger signals indicating the start of each step, for the underfrequency test.

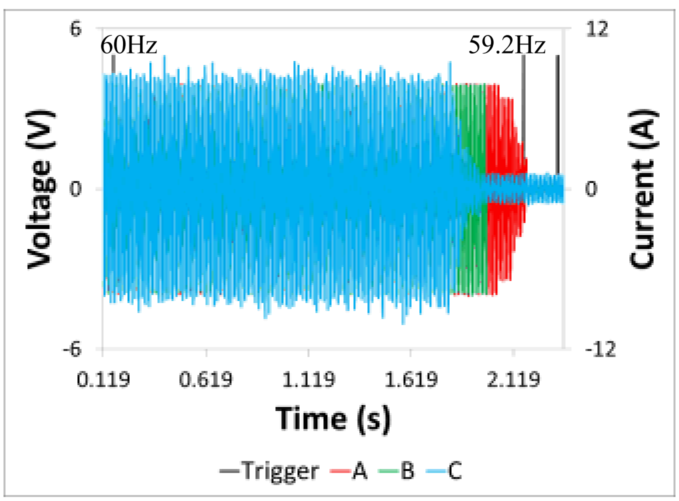

Fig. 11. 59.2Hz underfrequency trip time test.

In Fig. 11 the frequency was swept from 60Hz to 59.2Hz over two seconds and held there for 0.16 seconds (second to third trigger signals shown). Each string disconnected well before the third trigger signal limit of 0.16 seconds.

C. Reconnect following abnormal condition disconnect

The test for reconnect following abnormal condition disconnect is specified in IEEE Standard 1547-2005 [1], Section 5.10. This test verifies the functionality of the microinverter's reconnect timers, which delay reconnection to the grid following a trip event. The reconnect test was performed in conjunction with all of the abnormal voltage and frequency tests. Each microinverter model was designed to reconnect following an abnormal condition after 5 minutes of normal grid operating conditions. The reconnect time was confirmed to be correct for all microinverters in all cases, where each began reconnecting very near 5 minutes.

D. Anti-Islanding – Unintentional Islanding

The test for unintentional islanding is specified in IEEE Standard 1547-2005 [1], Section 5.7. This test will verify that the microinverter units and system cease to energize the grid when an unintentional island condition is present. The test will determine each unit's trip time.

Anti-islanding tests were performed on each individual string of microinverters as well as on the entire system. The tests are recommended at 33%, 66%, and 100% of rated power. Due to test period limitations, the tests were performed near solar noon of each test day under clear sky conditions to maximize power output. The string power output percentages varied between 76% to 88% during the individual string tests. The maximum power output percentage achieved during the total system tests was 82.3%. Results at other recommended output levels may vary.

Each anti-islanding test was performed using the utility through the AC disconnect and the configurable RLC load for power output matching. A power harmonics analyzer was used to configure the load to consume the real power output of the system while creating the 60Hz resonant frequency between the capacitive and reactive loads at a Q=1 [2].

Fig. 12 shows the total system anti-islanding test results at 82.3% of rated power.

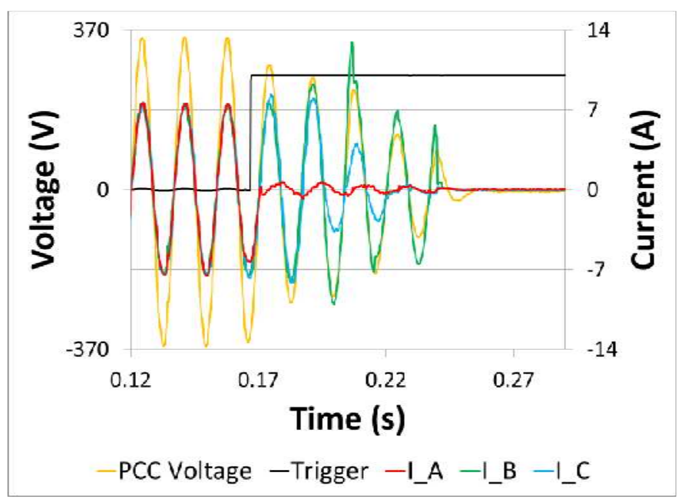

Fig. 12. Anti-islanding test, total system.

Fig. 12 shows that all strings disconnected in less than 5cycles/0.05s after the loss of the utility. This is well below the 120cycles/2s requirement. The individual string anti-

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islanding tests were very similar to the string results obtained in the system test.

IV. Conclusions and Significance

The microinverter isn't new to the solar industry, but the growth and implementation has gained significant momentum, fueled by the potential performance advantages and attributes inherent to the microinverter topology. These attributes include the removal of DC balance of system (BOS) requirements, reducing the presence of high dc voltage on a PV system, and the reduction of the impact that module mismatch and shading has on the power production of a PV system. While these attributes can have a significant impact on issues prevalent on residential PV installations, implementation can only be possible if microinverters can successfully interoperate with each other and the grid, and still meet grid standards. Test procedures for evaluating microinverter interoperability will provide a way to properly assess conformance.

The initial test results presented here indicate a need for further work. In particular, the disconnect failures found in the overvoltage and undervoltage operating points tests beg the question of whether these units would fail if tested separately from the other units or whether some interaction between the units is interfering with the expected performance. Verification would need to be performed by conducting the tests repeatedly and observing whether the same individual units fail every time, or a random mix of units. Once units that fail are identified, tests could be performed on the units individually to determine if the interconnection with other units is the cause of failure.

The limitations on the power output levels during the anti-islanding tests could also be expanded. Lower power level tests can be achieved most of the year with proper timing of the daily irradiance, or shading could be used to reach desired power levels. Reaching 100% nominal power output requires more season specific conditions to occur, such as lower temperatures, high irradiance, and more direct angle of incidence. Anti-islanding tests at other power levels may vary from those performed in section III.D and should be investigated.

Additional tests beyond those mentioned in this report could be beneficial to an interoperability assessment. These may include power quality assessments, such as harmonics testing [3], and other combinations of power conversion devices, such as string inverters and/or DC-DC converters. Another aspect to be considered is communication interoperability between manufacturer supplied power monitors. These monitors utilize power line carrier communication paths and ZigBee wireless communication to gather production data from microinverters in an array. Ensuring proper communication with only the desired microinverters in an array while in close proximity to other systems is required for accurate system power production data. Sandia plans to continue to explore the effect of multiple inverters on a distribution circuit with respect to conformance to grid standards for these devices.

References

[1] IEEE 1547-2005, Recommended Practice for Utility Interface of Photovoltaic (PV) Systems.

[2] UL 1741, Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources, November 7, 2005.

[3] IEEE 519-1992, Standard Practices and Requirements for Harmonic Control in Electrical Power Systems.

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