# IMPLEMENTATION AND TESTING OF ANTI-ISLANDING ALGORITHMS FOR IEEE 929 - 2000 COMPLIANCE OF SINGLE PHASE PHOTOVOLTAIC INVERTERS

Raymond M. Hudson[1], Tony Thorne[2], Fereydoun Mekanik[2], Michael R. Behnke[1], Sigifredo Gonzalez[3] and Jerry Ginn[3]

1) Xantrex Technology Inc. 161-G South Vasco Road, Livermore, CA 94550 USA
2) Xantrex Technology Inc. 5916 195th Northeast, Arlington, WA 98223 USA
3) Sandia National Laboratories, Bldg 833, 1515 Eubank Blvd, Albuquerque, NM 87123 USA

## ABSTRACT

Electrical system islanding occurs when the utility grid is removed but local sources continue to operate and provide power to local loads. This can present safety hazards and the possibility of damage to other electric equipment. Anti-islanding functionality is a key requirement for grid-interactive inverters used in PV systems that function as distributed generation sources. The IEEE Std. 929-2000 "Recommended Practice for Utility Interface of Photovoltaic (PV) Systems" (IEEE 929) [1] sets testing requirements for these systems which includes an anti-islanding requirement. UL has adopted this practice in UL-1741 [2]. This paper provides a description of Xantrex anti-islanding algorithms and examples of inverter testing. Inverters tested were the Xantrex SW with GTI and ST models. Testing was performed at the Sandia National Laboratories Distributed Energy Technologies Laboratory. Data is provided for single and multiple units with additional data on power quality.

## BACKGROUND

The intent of IEEE 929 was to define the technical requirements of PV system interconnection in a manner that could be adopted as a technical standard by individual utilities. Although IEEE 929 addresses a variety of issues, its most unique section deals with safety and protection functions, including the response of the PV inverter to abnormal utility conditions. The conditions of concern are voltage and frequency excursions, and the complete disconnect of the utility, presenting the potential for an unintended distributed resource island.

One of the objectives of IEEE 929 was to define a test procedure that can be used to confirm that a satisfactory anti-islanding technique is incorporated in an inverter. A manufacturer's label declaring an inverter to be non-islanding may not be sufficient to convince either a purchaser or an interconnecting utility that the inverter is indeed a non-islanding inverter. Therefore, it was necessary to develop a standardized test that an inverter with an adequate anti-islanding technique can pass, but which one that lacks such a technique will fail.

A significant effort was made to coordinate IEEE 929 with Underwriters Laboratories in the production of UL 1741 for "Static Inverter and Charge Controllers for Use in Photovoltaic Systems". This provides a test procedure that can be performed by an independent body to verify that an inverter intended for use with a utility-interconnected PV system meets the recommendations described in IEEE 929. The existence of these standards and procedures has greatly facilitated the implementation of grid-tied PV. The voltage and frequency limits for these standards are given in Table 1.

| UL 1741, First Edition, January 17, 2001 Revisions | | | |
|---|---|---|---|
| Voltage and Frequency Limits for Utility Interaction | | | |
| Condition | Voltage | Frequency | Max Trip Time |
| A | $0.5\ V_{nom}$ | $f_{nom}$ | 6 cycles |
| B | $0.5\ V_{nom} < V < 0.88\ V_{nom}$ | $f_{nom}$ | 2 seconds |
| C | $0.88\ V_{nom} \le V \le 1.10\ V_{nom}$ | $f_{nom}$ | - |
| D | $1.10\ V_{nom} < V < 1.37\ V_{nom}$ | $f_{nom}$ | 2 seconds |
| E | $1.37\ V_{nom} \le V$ | $f_{nom}$ | 2 cycles |
| F | $V_{nom}$ | $f < f_{nom} – 0.7$ Hz | 6 cycles |
| G | $V_{nom}$ | $f > f_{nom} + 0.5$ Hz | 6 cycles |

Table 1 IEEE 929/UL 1741 Utility disconnect requirements

IEEE 929 also addresses the important issue of power quality. There are requirements for the individual harmonics as well as the Total Harmonic Distortion (THD) of current at full rated power. These are based on the well-accepted IEEE-519 Recommended Practice and Requirements for Harmonic Control in Electrical Power Systems [3].

The scope of this paper discusses anti-islanding algorithms, how tests are conducted, test data and analysis of the results. The discussion includes examples using real data and tests with single and multiple grid tied Xantrex static inverters on a local grid, as well as "stacked" inverters for 120/240V residential applications.

Utility companies, new to this type of distributed generation utilizing renewable energy, have requested a test of multiple inverters connected to the same ac line. This request has also come from photovoltaic system integrators. The Sandia Report [4] that describes the development of IEEE 929 and its "non-islanding inverter" tests states: "Although multiple-inverter testing is not included in IEEE Std. 929-2000 or UL 1741, Sandia Laboratories will continue to perform multiple-inverter and single-inverter evaluations. The purpose of the tests is to continue to expand our knowledge base and to ensure that the single-inverter test is adequate for new inverter models." Additionally, an important aspect of the operation of a grid-interactive inverter is power quality. Harmonic content was measured and data is presented.

## TEST METHODOLOGY

Tests of grid-interactive static inverters were performed at Sandia National Laboratories in Albuquerque, NM, utilizing an anti-islanding test setup described in IEEE 929. The Distributed Energy Technologies Lab (DETL) is an extension of Sandia's photovoltaic inverter test facility. It is supported by the PV Program of the Department of Energy to evaluate power-conditioning equipment for manufacturers, utilities and end users. DETL has been used to measure the performance of distributed energy resources ranging in size from a few hundred watts to hundreds of kW. DETL test equipment includes photovoltaic arrays, battery banks, electrical loads (resistive, reactive, nonlinear, and motor), and ac sources (grid feeds, engine-generators, and solid-state arbitrary waveform generators). Xantrex Sun Tie (model ST) and Sine Wave II (with GTI) Series inverters were evaluated using test protocols developed at DETL for grid-tied inverters.

Figure 1 shows the test configuration for the anti-islanding test.

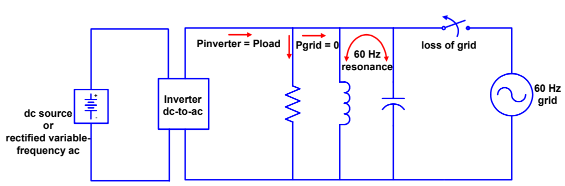


Figure 1. Islanding Test Configuration

The components that make up this test stand are :

| | |
|---|---|
| Resistive: | Avtron 150kW 3ph |
| Inductive: | Avtron k841 225kVar 240/480 60Hz |
| | Avtron 0-3.75kVar (variable) |
| Capacitive: | GE PFC 50kVAr 3ph 480V 60Hz |
| | Variable 0-14kVar 240V 60Hz |

A LabView™ Data Acquisition system is used to gather data and control this system. It monitors and calculates the ratio of power generated to load power (Pg/Pl), removes the utility and calculates the run-on time from the moment the contactor is opened to the time the inverter current drops to 0.1 amp peak which indicates successful system disconnection.

The load values used in setting up the RLC islanding test determine the real power from the inverter as well as the resonant condition. The quality or "Q" factor is calculated using the following equation (1):

$$Q= \sqrt{\frac{C}{L}} \text{ or } \frac{Vars}{Watts}. \qquad (1)$$

The RLC islanding tests are to be conducted at a quality factor of up to 2.5 .

The LabView™ system also calculates the %total harmonic distortion (%THD) for the voltage and current at various power levels. The %THD computation is made using the following equation (2).

%THD=100*sqrt[A(f2)^2+A(f3)^2+....A(fN)^2]/A(f1) (2)

where:

A(f1) is the amplitude of the fundamental component,
A(fN) is the amplitude of the Nth harmonic, and N is the number of harmonics in the measurement. THD is defined by IEEE 519 as including the $50^{th}$ harmonic and below (N=50).

THD is a key measure of grid system performance. The standards are based on this measurement at full power (which corresponds to Total Demand Distortion or TDD). Power quality data is presented for the systems tested in this activity.

## ANTI-ISLANDING ALGORITHMS

Islanding, as explained earlier, occurs when an inverter continues to provide power to a disconnected section of the grid during a utility blackout. If the loads become balanced, resonating with the line frequency (50 or 60 Hertz) and the inverter fails to detect the loss of grid power, islanding occurs. There are various algorithms that have been used to detect islanding [5], [6]. Essentially, these algorithms provide a disturbance that will move the system out of resonance. It is common that the fault detection is then made by the standard over and under frequency and voltage checks that are required by IEEE 929. The algorithms used by the Xantrex ST and SW with GTI are described in the following section.

### STXR Anti-Islanding Approach

The Sun Tie series platform is based on an isolated DC-to-DC converter from the photovoltaic array to a dc link, and then a second stage DC-to-AC inverter for the output. The output is controlled by a line referenced, average current mode controller with feed forward design. This type of system design provides a natururally unstable approach to anti-islanding which forces the AC current onto and in reference to the line voltage itself. This type of control requires an active power balance without the use of internal line frequency reference clocks, or any other method to control frequency. Ultimately, the power would be driven off balance no matter the resonant Q factor, or the stability of either frequency or voltage.

**SW with GTI Anti-Islanding Approach**

The Xantrex Grid Tie Interface (GTI) device is intended to implement the power quality and anti-islanding functions for the SW series of inverters. To prevent islanding, the GTI creates a one Hertz signal that modulates the magnitude of the phase shift around its SELL-mode set point value. When grid power is available, the phase shift has no more effect than a slow variation of the current around the average value, and does not change the power being sold to the grid.

When grid power is lost and the load is resonating, the GTI's phase modulation throws the resonance off balance and modifies the resonant voltage frequency. This change of voltage and/or frequency is detected by the voltage sense or frequency sense of the GTI, and immediately initiates a shutdown signal to the inverter system. In less than two seconds, the inverter stops selling power, thus eliminating the potential for islanding.

**SW With GTI TEST RESULTS**

**Single Unit**

Testing to the UL 1741 standard has identified an issue with some voltage source inverters and a potential islanding condition. In response to this condition, a new addition to the Xantrex Sine Wave series products has been introduced. This new active filter assembly, called the Grid Tied Interface (GTI) was integrated into the present SW II series platform to provide active anti-islanding features complimented by side benefits such as reducing voltage and current total harmonic distortion.

When the GTI is connected and the inverter SELL mode is selected, the microprocessor of the GTI takes control of the SW and operates the inverter SELL feature. As shown in Figure 2, the GTI unit contains an automatic transfer/shorting relay (marked as the buy/sell relay), which the SW uses to disconnect the GTI from the circuit when it is not needed, for example, when the SW is charging batteries from the grid. This is also used to disconnect the GTI so that it does not represent a phantom load or parasitic loss to the system. During a blackout or any time the SW is powering house loads directly, the GTI is not in the power circuit and does not represent an efficiency loss.

The second GTI Bypass Relay shown in Figure 2 connects the loads to grid power during sell mode operation only. When a grid outage occurs, the GTI bypass relay transfers back to inverter output providing backup mode operation.

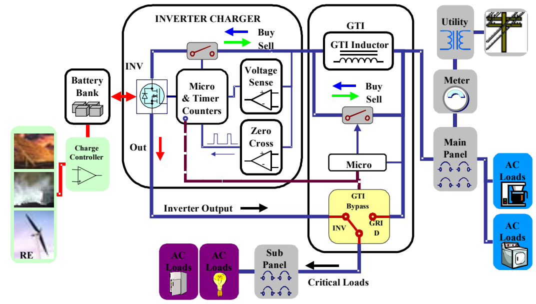


Figure 2. Block Diagram of SW with GTI

The SW 5548 unit used in this series of tests has a 5.5kW rating that employs a nominal 48V battery. Figure 3 shows the data obtained during the longest islanding duration. The data presented in figure 3 are waveforms of the line voltage, current from the inverter and the trigger signal from the auxiliary contacts on the motor starter, which signifies the removal of the utility and start of the islanding test.

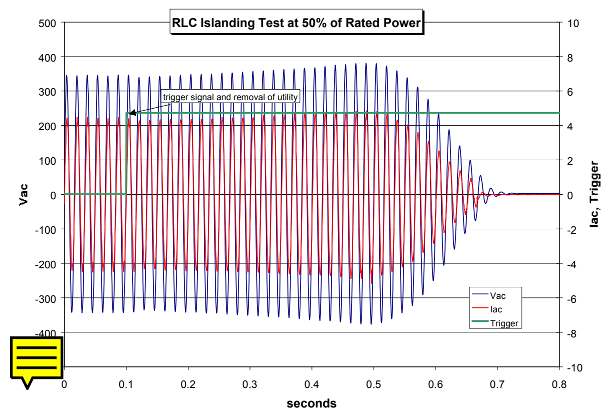


Figure 3. SW 5548 with GTI Anti-Islanding results

Just prior to interrupting the utility, values are recorded for the power generated by the inverter and for the ratio of power generated to load power (Pg/Pl ratio). Following the test, the time required for the inverter to disconnect after removal of the grid is also recorded. The quality factor (Q) is defined as the ratio of reactive power to resistive power, and is a measure of the tendency of the circuit to continue to oscillate once the grid is removed. IEEE 929 sets an upper limit for Q of 2.5. Figure 4 shows the disconnect times and Pg/Pl ratios versus Q factor for each of the islanding tests performed on the SW 5548 with GTI.

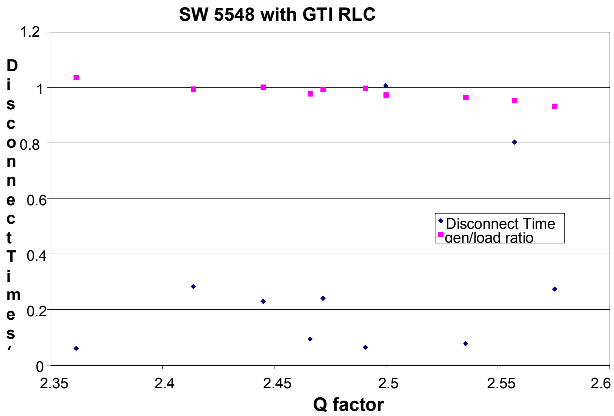


Figure 4. SW 5548 With GTI multiple disconnect tests

The Xantrex SW 5548 inverter with GTI was set to SELL mode and operated at 4 different sell levels: 12A, 23A, 35A, and 46A. This correlates to approximately 25, 50, 75 and 100% of rated power. Figure 5 shows the THD levels on the voltage and current while selling power to the utility. At rated power, the current THD level is well below the 5% maximum allowed by IEEE 929.

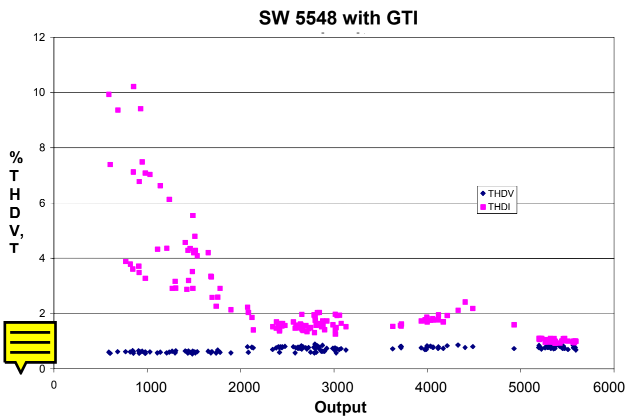


Figure 5. Percent THD of SW 5548 with GTI

**Stacked Units**

Two SW 5548 inverters with GTI devices were connected in series in a master/slave control configuration for 11kW operation. This series stacked configuration provides 120/240 volt split phase outputs, representative of residential applications. The stacking system utilizes a control communications cable between the units to provide 180-degree output synchronization for residential applications.

The anti-islanding features of each inverter operate independently from each other, but this test demonstrates the performance of the active anti-islanding controls at the single unit 120-volt operation, and the 120-120/240-volt stacked configuration during RLC resonant load testing per IEEE 929.

The RLC 60 Hz resonant islanding tests were conducted on the series stacked inverters. Five islanding tests at 50, 75 and 100% of rated power were conducted with this configuration. The longest islanding duration was less than 10 cycles. Figure 6 is a plot of the longest islanding duration captured when conducting the tests at rated power.

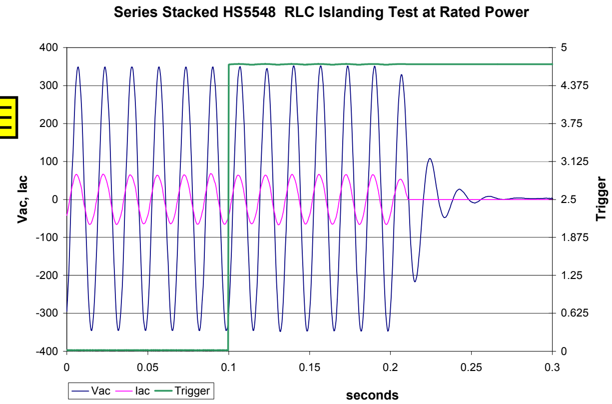


Figure 6. Stacked SW5548 with GTI Anti-Islanding results

Figure 7 shows the disconnect times and Pg/Pl ratios of the five islanding tests at rated power. The plot shows the inverters responded rapidly (on the order of 0.1 seconds) in this configuration.

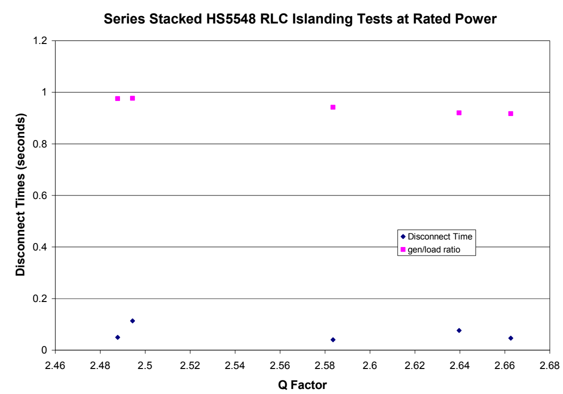


Figure 7. Stacked SW 5548 with GTI multiple disconnect tests.

Figure 8 shows the THD output of the stacked inverters. Operating the inverters to rated power drew large currents from the battery bank, causing the battery voltage to approach 45Vdc from its nominal value of 48 Vdc. In spite of the lower battery voltage, the THD remained below the 5% requirement at rated power.

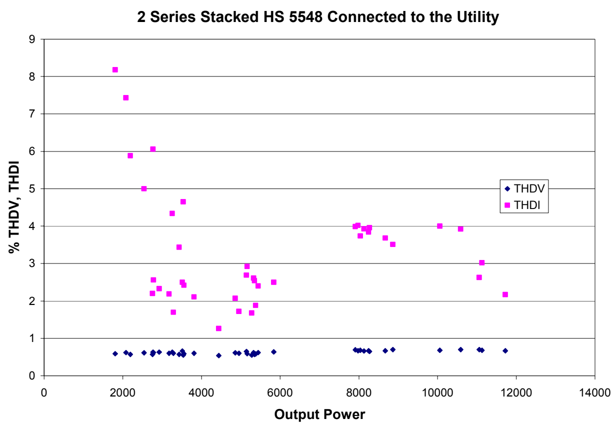


Figure 8. Percent THD of stacked SW5548's with GTI

## ST TEST RESULTS

### Single Unit

The Xantrex ST series was developed as a photovoltaic inverter for utility interactive operation. All utility interactive features were designed into the ST system. The anti-islanding results of testing at the DETL are shown in Figures 9 and 10 for time domain and multiple disconnects respectively.

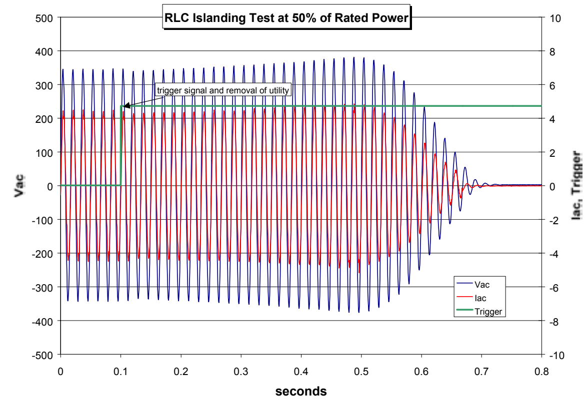


Figure 9. ST Anti-islanding results

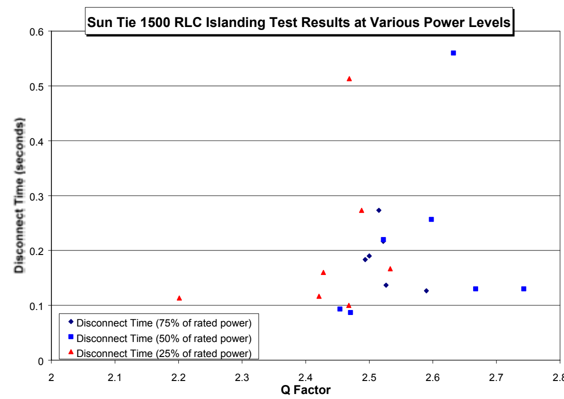


Figure 10. ST multiple disconnect tests

The harmonic performance of the ST is show in Figure 11. At rated power, it can be seen that the current THD level is well below the 5% limit of IEEE 929.

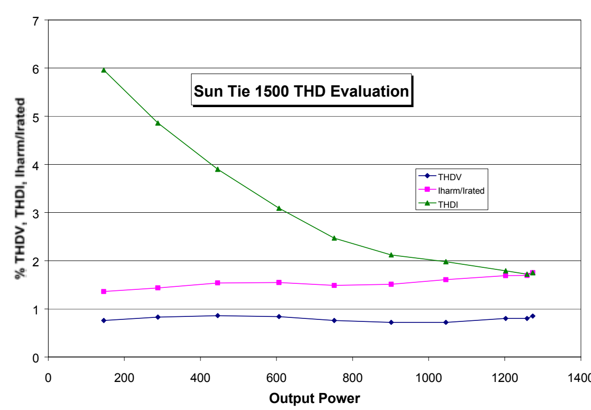


Figure 11. Percent THD of ST

## Multiple Units

The RLC 60 Hz resonant islanding tests were conducted with four ST units connected to the same point in the distribution system. Time domain results for the longest run-on are shown in Figure 12. This shows that all four units disconnected within the 2 second limit of IEEE 929.

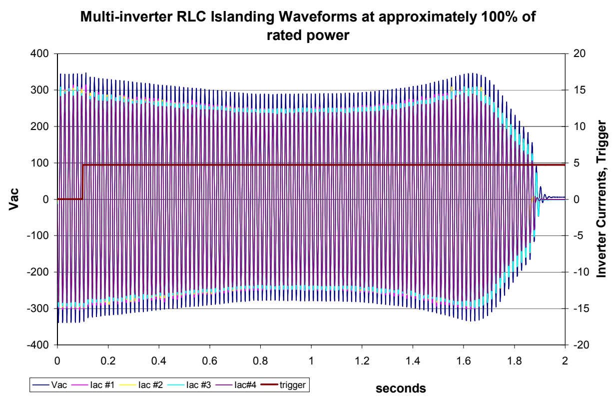


Figure 12. Multiple ST Anti-Islanding Results

## CONCLUSIONS

The IEEE Std. 929-2000 Recommended Practice for Utility Interface of Photovoltaic (PV) Systems was developed to provide guidelines to the PV industry as well as standardize a practice for inverter manufacturers to follow. An essential part of this document describes standards created for static, utility-tie inverters in order to safely connect to utility grids and prevent inadvertent islanding conditions.

The test results demonstrate the importance and validity of IEEE-929 and UL-1741 single inverter testing, such that multi inverters in a common grid do not, nor cannot, create an island condition. The capabilities of the Sandia DETL are demonstrated by the ability to gather accurate data to confirm the conformance of PV inverter systems to this standard. The Xantrex ST and SW with GTI were demonstrated to meet this standard in multiple configurations.

## REFERENCES


[1] IEEE Std 929-2000, IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems, Institute of Electrical and Electronics Engineers, Inc., New York, NY.

[2] UL 1741, Std 1741 , Static Inverter and Charge Controllers for Use in Photovoltaic Systems, Underwriters Laboratories Inc., Northbrook, IL.

[3] IEEE Std 519-1992, IEEE Recommended Practice and Requirements for Harmonic Control in Electrical Power Systems, Institute of Electrical and Electronics Engineers, Inc., New York, NY.

[4] Sandia Report SAND2000-1939, Development and Testing of an Approach to Anti-Islanding in Utility-Interconnected Photovoltaic Systems,". Stevens, John, et al

[5] G. Kern, R. Bonn, J. Ginn, S. Gonzales, "Result of Sandia National Laboratories Grid Tied Inverter Testing", *Proceedings of 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion*, Vienna, July 1998.

[6] US Patent 6219623, "Anti-islanding Method and Apparatus for Distributed Power Generation", assigned to Plug Power, Inc., Latham, NY