Microgrid Application of Four-Leg Three-phase Inverter

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***Abstract*— *The On-grid inverters use energy from DC sources to feed AC consumers, and also the main grid whenever there is a surplus of energy, as distributed energy resources. A caveat of on-grid inverters generally implied by worldwide electrical standards imposes that whenever a fault occurs on the main grid, local generation must be shut off to prevent unintentional islanding. However, there are some applications where distributed resource systems could improve reliability, and on-grid inverters with off-grid function can continue to operate even when grid power outages occur, known as intentional islanding. Today's micro-grids have better sensing capabilities and superior semiconductor technologies that allow faster response times and higher maximum ratings, improving micro-grid equipment isolation and control capabilities. In this paper, we review anti-islanding tests performed on on-grid inverters with off-grid function in Brazil for conformity assessments and present a case study of a 20 kW hybrid inverter.*

***Keywords*— hybrid, inverter solar, distributed, generation.**

I. INTRODUCTION

The distributed generation (DG) market in Brazil is constantly growing, reaching 1423,5 MW of installed capacity in the grid in the third quarter of 2019, with a 111,07% growth in volume compared to 2018, according to the study published by Greener [**Error! Reference source not found.**] (based on data from the Brazilian Revenue Service, and Brazilian Electricity Regulatory Agency – ANEEL), where growth continues at high rates, despite local and foreign economic troubles. In this same sense, Brazilian Energy Balance - 2019 (year 2018) [31] publishes information regarding the micro and distributed mini-generation of electric energy, whose growth was stimulated by regulatory actions, such as that which establishes the possibility of offsetting the surplus energy produced by smaller systems (Net Metering).

Among the different components of distributed resource systems, a large cost is due to the power inverter, which transfers power from a local DC source to AC consumers and the main grid. System input is usually a high voltage source where voltage reduction is generally desired for powering standard AC equipment.

There are two types of power inverters available in the Brazilian market when considering main grid connection or isolation: off-grid and on-grid inverters. Off-grid inverters are intended to provide power to isolated consumers from local DC sources, such as photovoltaic energy, in what is known as island mode operation. On-grid inverters use power from DC sources to feed AC consumers and also the main grid whenever there is a surplus of energy. This allows the user to earn revenue usually in the form of energy bill deductions.

A caveat of on-grid inverters generally implied by electrical standards imposes that whenever a fault occurs on the main grid, local generation must be shut off to prevent unintentional islanding. However, there are some applications where distributed resources can improve reliability in the case of intentional islanding, as further detailed in IEEE 1574.4 [[3]]. Although not yet officially available in the Brazilian market, on-grid inverters with off-grid function allow both modes of operation, connected or isolated from the main grid. Figure 1 presents a hybrid inverter topology with on-grid operation and off-grid function for critical loads, powered by a photovoltaic source and an additional battery bank for energy storage.

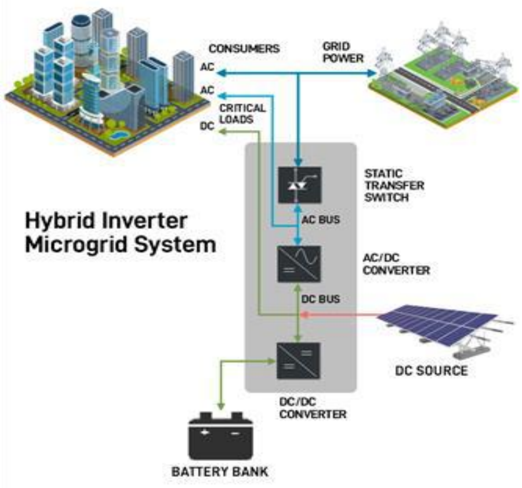

Fig.1. Proposed hybrid inverter grid system.

Despite uncertainties regarding regulation and certification, hybrid inverters are very sought-after in the Brazilian market and there is a considerable future demand for purchase, according to a study by Greener in 2018 [[2]]. Also, today's micro-grids have better sensing capabilities and superior semiconductor technologies with faster response times and higher maximum ratings, where micro-grid equipment isolation and control capabilities allow safer and more reliable operation ever than before. Strict test procedures defined by Brazilian conformity assessment regulations aim to ensure safety and quality to the hybrid inverter market. In this paper, we review anti-islanding tests performed on on-grid inverters with off-grid function in Brazil for conformity assessments and present a case study of a 20 kW prototype.

II. REVIEW OF ANTI-ISLANDING CONFORMITY ASSESSMENTS

Islanding is the transfer to a condition where the electrical installation, including the load and the generator, is isolated from the rest of the power grid [[4]].

This is a situation that electricity distribution companies should avoid. In some cases, intentional islanding may occur where the island is created by the distributor to isolate certain regions from the main power grid. Unintentional islands, however, also occur when network segments that contain private generation and loads are beyond the control of distributors.

The occurrence of unintended islands in distribution networks is a major concern for network operators because they can cause accidents to workers performing line maintenance, assuming the line is designed for maintenance. A study [[8]] attempts to show the additional level of risk for consumers and grid maintenance staff for systems with photovoltaic energy in low voltage distribution networks. [[8]]. Therefore, it is very important to develop anti-islanding measures for DG systems.

Different methods for islanding detection have been developed in recent years [[9]-[26]], among them are passive techniques [[13]-[18]], active techniques [[19]-[22]], hybrid techniques [[23]-[24]], and other notable solutions [[25]-[26]]. No island protection system is fully reliable and all methods have their advantages and disadvantages [[27]-[28]], mostly based on dependability and security, operating time, impact on grid, cost, and adaptability to grid characteristics [[28]].

Among the available techniques, the one used by the inverter that will undergo tests presented in this article is a passive technique. Passive techniques are based on the monitoring of electrical parameters such as voltage, current, frequency, phase and harmonics, as these parameters often vary when the system is in an island condition. The advantages of this technique are its low cost of implementation, the non-introduction of disturbances in the electrical system, as well as being much faster than other techniques for islanding detection [[29]]. As disadvantages, there is the inability of the technique to detect islanding during balanced islanding and a large non-detection zone (NDZ) [[29]-[30]]. Further studies specific to the power grid in which your system is inserted in are important as to settle the threshold values of anti-islanding measures and differentiate such problems from other system disturbances.

As there is no standard for voltage inverters that work with on-grid and off-grid functions, other standards have been adapted [[4]-[6]] to perform conformity assessments . In this paper, we considered most important for consumer and grid safety, parameters such as: undervoltage disconnect time, off-grid connection, network reconnect, and electrical parameter maximum values.

III. METHODOLOGY

The inverter test scheme follows the circuit shown in Figure 2. Since the inverter test is relevant only to the AC

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equipment, the DC / DC converter and DC load have been disconnected.

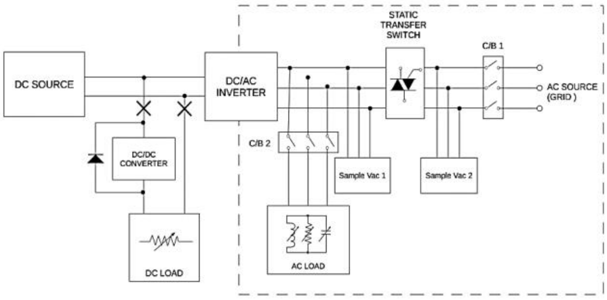

Fig.2: Hybrid inverter test schematic.

When the system is disconnected from the grid, the circuit breaker C/B1 is open, C/B2 is used to determine the initial conditions of the AC load and DC source at the fundamental frequency (60 Hz). The following electrical parameters are measured: Rated output voltage; Operating voltage range; Output power; Output Frequency and Power Factor.

Fig.3: Presented 20kW hybrid inverter and test-bench instruments.

According to the standard [[4]], an oscilloscope is required to measure voltage and current waveforms must have a sampling rate well above the signal frequency to perform time measurements and analysis with precision less than or equal to 1% of nominal voltage. The instruments used in the tests consisted of the Power Quality Analyzer (PQA) Fluke Series II 434 and Oscilloscope LeCroy WaveSurfer 104MXs-B. The hybrid inverter that was tested can be seen in Figure 3.

When the system is powered by the DC source and connected to the network (closed C/B1 and open C/B2), a simulation of inverter behavior begins in the case of a power failure, to test islanding performed by the static transfer switch.

To measure the electrical parameters at inverter output and those coming from the grid, there are two voltage and current sampling modules Sample Vac1 and Vac2 positioned at each end. When the Sample Vac2 signal demonstrates anomalous behavior, the static switch should open disconnecting consumers from the grid.

The parameter that indicates the anomalous behavior for any phase characterizing the mains fault event occurs when the grid voltage value is below 85% the inverter's nominal output voltage. This procedure is based on undervoltage tests of existing on-grid inverter standards.

After the mains fault event, the static transfer switch triggers, isolating the inverter to continue the waveform with steady-state amplitude, frequency and phase. The measurement performed for the test is the time difference between the mains fault event and isolated steady state configuration. The considered stability regime has the following electrical characteristics: effective voltage value above 85% and below 110% of nominal voltage, and frequency within the nominal range (± 5%). The time between mains fault and isolated steady state should be equal to or less than 20 ms.

Being in an isolated steady state, is the consumer powered only by the DC/AC inverter, the Sample Vac 1 signal is monitored and compared to the Sample Vac 2 signal. When the grid returns to normal, the inverter identifies the phase difference between the two signals for synchronization of the waveforms.

Synchronization is the gradual delay of the inverter's waveform and change in frequency until Sample Vac 1 matches Sample Vac 2 in frequency and phase. When both signals are synchronized, the static transfer switch is closed, consuming AC power over the network. Once the static switch is closed, the inverter resumes normal operation.

Another parameter measured for the test is the time difference between the network return event and normal operation. The time between events should be between 20 and 300 s, as recommended by the standard [[4]]. A summary of the different test parameters is shown below (Table 1).

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Table 1. Summary of the behavior of the switching system to be analyzed.

Measure\ Event	Network Anomaly (grid fault)	Island Mode (isolated steady state)	Normal Operation
RMS Voltage	Vrms < 85%Vr1 Vrms > 110%Vr	85%Vr< Vrms <110%Vr	85%Vr< Vrms <110%Vr
Acceptable interval for transition to next state	20 ms	20 to 300 s	-

IV. RESULTS

The circuit of Figure 2 was assembled and when the C/B2 switch was closed, the values of the nominal output voltage, power, frequency and power factor were measured, as shown in Figures 4-6.

Fig.4: Power factor measurement

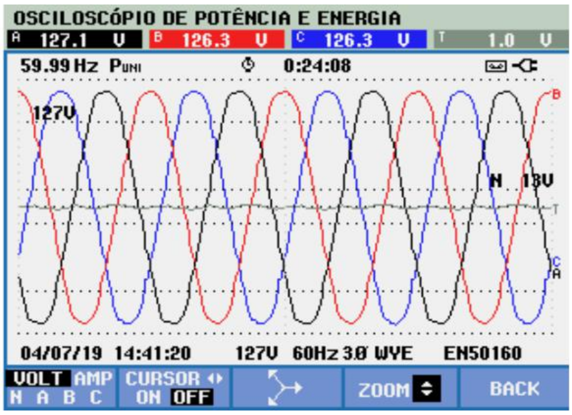

Fig.5: Output phases and neutral voltage waveforms.

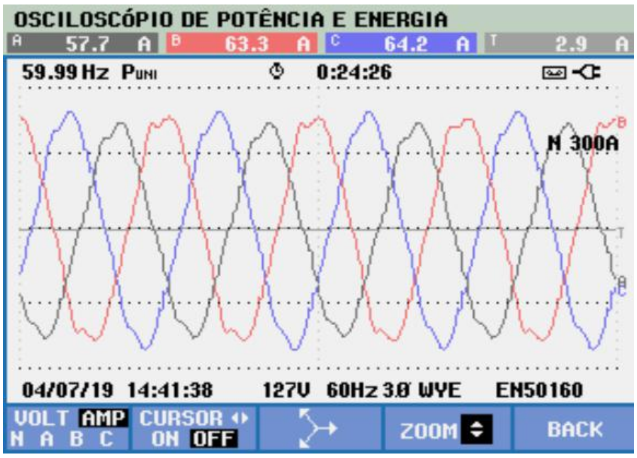

Fig.6: Output current waveforms.

The time-domain of tests with disconnection from the grid due to undervoltage and reconnection can be seen in Figures 7 and 8.

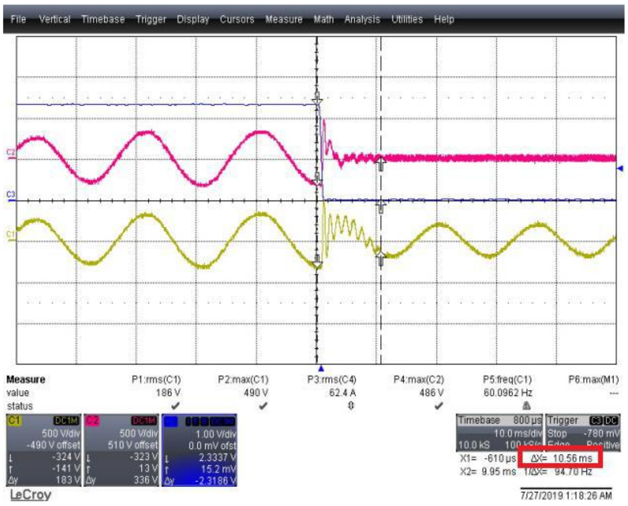

Fig.7: Time-domain of disconnection test

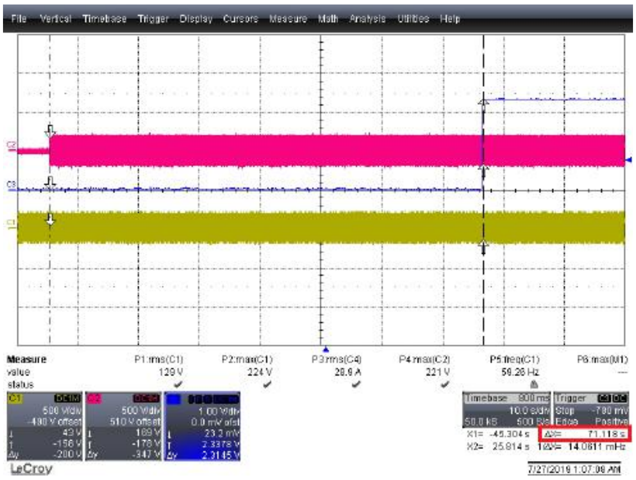

Fig.8: Time-domain of the reconnection test

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Figure 7 shows the network signal (CH1-pink), inverter power (CH2-green) and static transfer switch control signal (CH3-blue); in the event of a mains failure, in the criteria previously described in the Methodology section: Effective Voltage above 85% and below 110% of rated voltage and frequency within specified range (± 5%), the inverter isolates consumers from the grid and continues the waveform. After a 10.56ms interval from the network fault event, the inverter reached steady-state output and fed consumers with off-grid power.

Figure 8 displays the reconnection time measurement triggered when the grid returns to normal conditions and the inverter must synchronize the isolated waveform in phase and frequency. After a 71.118s interval from the network return event, the inverter resumed normal on-grid operation. The reconnection test can also be seen in Figures 9-12, which better depict the process of synchronization.

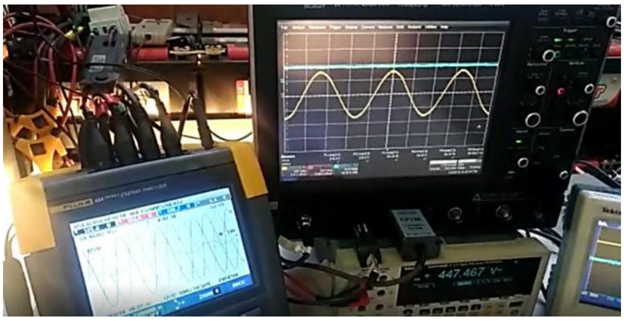

Fig.9: Grid (Sample Vac 1 - Yellow) present during normal on-grid operation (DC Source - Blue).

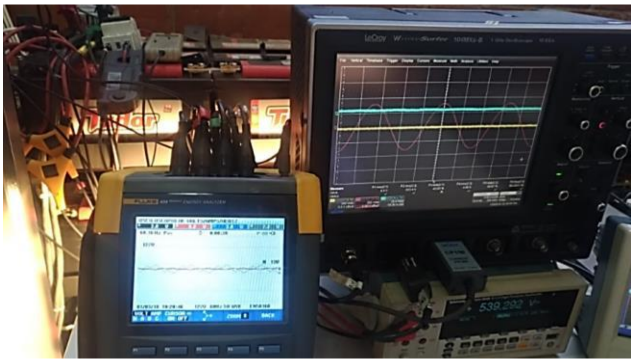

Fig.10: Grid fault event occurs, static transfer switch isolates inverter in off-grid operation (Sample Vac 2 - Red).

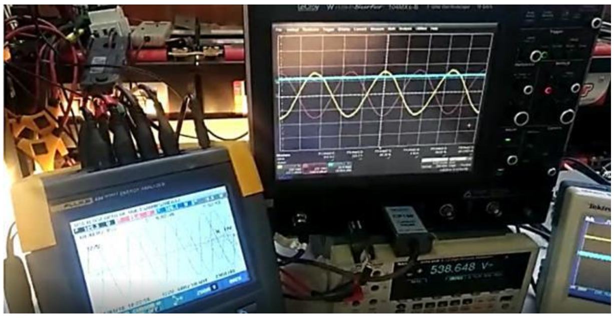

Fig.11: Grid and inverter output unsynchronized, phase and frequency must be matched to close the static transfer switch.

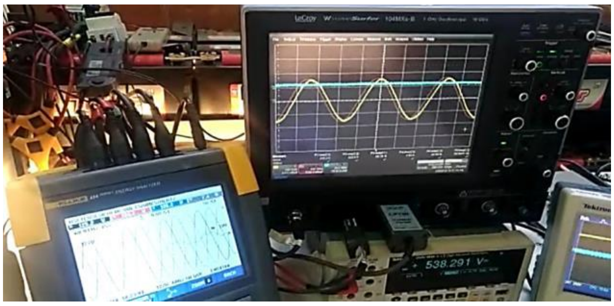

Fig.12: Inverter output synchronized to grid, static transfer switch can now be closed.

V. DISCUSSION

Analyzing the tests, the results found were satisfactory. Time-domain analysis for disconnection from the grid due to undervoltage (10.56ms) and reconnection (71.118s) are within the acceptable intervals for transition to Island Mode (< 20ms) and to Normal Operation (between 20 and 300s). Intervals may vary considering the convergence of the synchronization algorithm and initial conditions. In conformity testing, it is necessary to consider the worst case, the phase difference of 180° which is most distant. For the transition to Normal Operation, a software delay must be introduced if the synchronization is less than 20s, to meet conformity requirements.

The tested inverter was able to disconnect from the system when distortion was introduced to the grid reference. When the grid had a rated voltage below 85%, the static switch opened automatically, and the inverter left the grid. However, it is important to note that according to [[4]] the anti-islanding tests should also verify that the inverter transitions to island mode when the reference is removed from the system.

The inverter was able to reach the stability level in 10.56ms after the grid fault event, which is a very satisfactory result for the concept of a hybrid inverter. In order to make intentional islanding viable for on-grid inverters that have an off-grid function, the stability and speed of the transitions must be optimal, with least impact to consumers and grid operation.

VI. CONCLUSION

We present a simple methodology for testing hybrid on-grid/off-grid power inverters according do conformity assessments, contributing to the development of distributed generation systems.

In order to certify distributed generation equipment, it is necessary to submit them to the tests specified by [[7]], not specifically designed for hybrid inverters. Therefore, we believe that the developed tests can contribute to the development of certification processes for hybrid inverters in Brazil.

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The authors declare no conflict of interest.

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