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Development of an electrical characterization device for single-phase pv grid-connected inverters

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Abstract

The Grupo en Energías Renovables at the Universidad Nacional del Nordeste (GER-UNNE) developed a testing system for the characterization of grid-tied inverters with rated power up to 4.4 kW. The test procedures followed the guidelines established by EN 50530:2010, IEC 61727 and BS 50438:2007. This paper presents the development of the instrumental and the determination of the measurement uncertainties associated to the experiment by comparison with results obtained from an inverter test facility built at the Solar Energy Laboratory at Universidade Federal do Rio Grande do Sul (LABSOL-UFRGS), Brazil. The error associated to the inverter conversion efficiency, with the loading ranging from 10% to 100%, was shown to be lower than 1%. The error in the efficiency error determination with partial load under 10% is lower than 8%.

Keywords: *Grid Tied Photovoltaic Systems; Inverter; Instrumentation.*

1. Introduction

Grid-connected photovoltaic systems are presented today as an alternative to promote the implementation of distributed generation [1]. Because of its intrinsic modular nature it can be included as electricity generators in low voltage distribution networks being able to feed loads that, during certain periods of the day, would demand more energy than it can be delivered by the conventional grid. The peak of the typical demand profile in the Northeast of Argentina coincides with the period of maximum solar irradiance, hence, with the maximum generation of the photovoltaic system [2]. Therefore, the use of such power systems can attenuate those consumption peaks helping to minimize the overload suffered

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by transformers and distribution lines during periods of high demand thus avoiding the need for reinforcing the grid with the consequent economic costs implied. The energy provided by grid-connected photovoltaic systems improves the quality of the electricity supply at the distribution lines by including a renewable and sustainable method of power generation.

In Argentina, in spite of the governmental act for the implementation of power generation systems using renewable resources (National Law No. 26.190, 2006), the installed grid-connected photovoltaic generation capacity is negligible. Therefore, so far there has not been developed a normative regulating the characterization of grid-tied inverters and its interaction with the distribution grid. This is the main reason international standards are employed for any work carried out in this field.

Grid-tied inverters can be characterized by determining the efficiency by which the energy available at the photovoltaic generator is converted to the conditions required for the distribution of electricity in the grid. The overall efficiency of an inverter is the product of two components: the conversion efficiency and maximum power point tracking (MPPT) efficiency [3]. The European Standard EN 50530:2010 "Overall Efficiency of Photovoltaic Inverters" [4], presents a methodology for determining these efficiencies.

The British Standard BS 50438:2007 "Requirements for the Connection of Micro-Generators in Parallel with Public Low-Voltage Distribution Networks" [5], It includes specifications on the quality of the energy injected to the grid concerning parameters such as current harmonic distortion, fluctuations in voltage levels, power factor, frequency, flicker, etc. Moreover, this standard proposes a methodology for assessing which (and how fast) protection devices should act in situations of network failure (variations of voltage and frequency outside the permitted range). Another standard that deals with the same subject is the IEC 61727: "Photovoltaic (PV) Systems - Characteristics of the Utility Interface" [6].

To implement the characterization of inverters, in order to determine the parameters required by the standards it is necessary to measure and store some electrical parameters, particularly the voltages and currents at the inverter input throughout its operating range. To acquire these signals it is desirable a high sampling rate and determine the temporal behavior of each of these parameters by subsequent digital signal processing.

Considering the aforementioned reasons, the Gurpo de Energías Renovables (GER) of FACENA-UNNE, developed a system to measure, store and process the necessary data for the characterization of grid-tied inverters. This development is part of a project for the study and implementation of distributed generation (DG) using grid-connected photovoltaic systems meeting the conditions set by the EN 50530:2010, IEC 61727 and BS 50438:2007. This paper describes the developed system and the comparison the gathered data with the results obtained at the inverter test facility of the Solar Energy Laboratory at Universidade Federal do Rio Grande do Sul (LABSOL-UFRGS), Brazil. The testing and calibration of the equipment were performed within the framework of a cooperation project between Argentina and Brazil.

2. Electric characterization system

As mentioned before, in order to characterize a grid-tied inverter and its interaction with the low-voltage distribution grid one must measure and store the voltage and current values at both the ends of the inverters, input and output, for different operating conditions. These data can provide the input and output power, the power factor of the injected current, the harmonic distortion and the conversion efficiency, among other parameters. For each of the variables involved, the time interval between samples must be short enough to obtain (in compliance with the sampling theorem) a correct image of the measured variables [7]. Since the voltage and current signals at the input side of the inverter (i.e. provided by the photovoltaic generator) are DC and present relatively slow variations (slower than 1 ms), a proper acquisition can be attained without the need of a high sampling rate. However, the AC signals at the output side of the inverter must be acquired at a higher sampling rate (1.6 to 6.4 kS/s as suggested by IEEE P1159.1, 2000) [8] with the purpose of determining the harmonic content signal by means of digital signal processing, that is, using digital filters, fast Fourier transform (FFT), etc. Furthermore, to evaluate the dynamic behavior of the inverter protection devices it is necessary to capture the transients at the output signals during each generation interruption caused by the inverter. Thus, a measurement system with a higher sampling rate (6.4 kS/s) is required for this assessment.

Following these premises, a data acquisition module (USB6009, National Instruments) was used as the main measuring element. This module features four A/D (analog to digital) channels that can acquire differential signals with a resolution of 14 bits, maximum sampling rate of 48 kS/s and a maximum voltage error percentage of 1.2 %. The module includes programmable gain amplifiers (PGA) allowing conversion of voltage signals with amplitudes ranging from ± 25 mV up to ± 20 V. Nevertheless, more accurate measurements can be obtained when setting the measurement channels with the end of scale at ± 4 V [10] with external conditioning circuitry developed to suit the amplitudes of each of the signals to this range. The module is controlled by a program written in Matlab [9].

Figure 1 depicts a block diagram of the developed system for the grid-tied inverter characterization, showing the points where the measurements are taken.

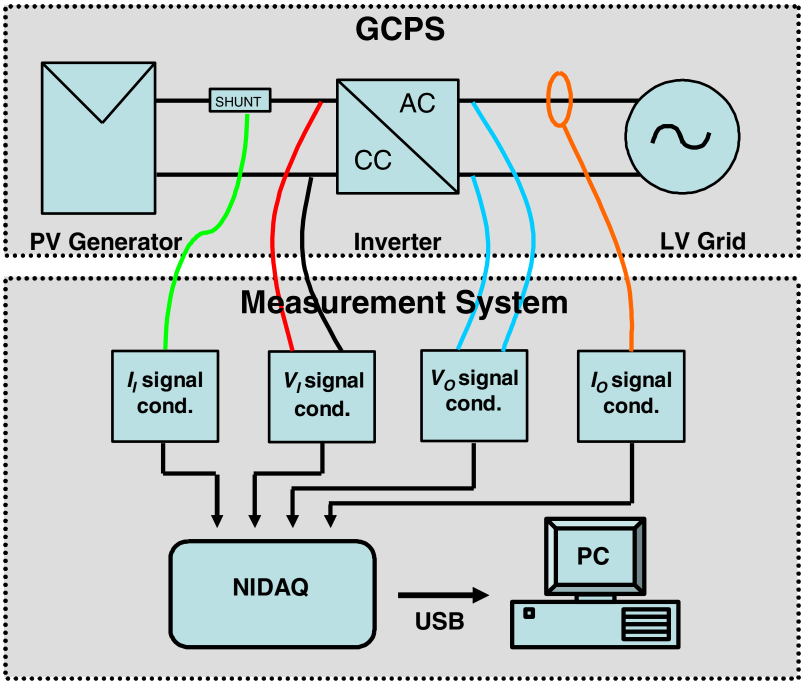

Fig. 1. Block diagram of the developed system for the grid-tied inverter characterization.

Because the voltage imposed by the PV generator to the input of the inverter (V_I) is usually high (above 100 V_{DC}) a resistive divider was used to adapt this voltage to suitable levels at the input of the acquisition module. The current at the inverter input (I_I) is sensed by a resistive shunt (class 0.5 with a ratio of 25 mV/60 A). The signal from the shunt is amplified by a factor of 100 by means of a double stage instrumentation amplifier. This circuit was implemented with two cascaded stages of amplification (each one with the gain set to 10) using instrumentation operational amplifiers and high quality resistors. Thus, the maximum acceptable voltage and current at the input of the inverter under test is 400 V and 25 A respectively.

In order to avoid parasitic currents between the input and the output of the inverter, the measurement system was implemented with galvanic separation between AC and DC sides. Therefore, to measure the AC voltage at the inverter output (V_o) a voltage transformer (*VT*) class 1 with 20:1 ratio and maximum phase error of 1% was employed. A current transformer (*CT*) associated with a load resistor was used to measure the AC output current (I_o). This sensor is capable to measure currents up to 20 A with an error of amplitude and phase of 1%. The characteristic of this transducer limits the maximum measured power to values about 4.4 kW and 2.2 kW for inverters designed to be used in 220 V_{AC} grids and 110 V_{AC} grids respectively. This limit was imposed in order to keep the accuracy of the AC current measurement at low current levels, considering the low power ratings of the inverters to be tested. However, this range can be easily extended to 10 kW by changing the current probe for another with a higher maximum current (50 A).

The voltage and current transformers were experimentally characterized in order to obtain their frequency response (IEEE P1159.1, 2000). The results obtained were used to fit correction curves allowing the determination of the errors in amplitude and phase of the harmonic components as a function of the frequency. These adjustments were introduced to the algorithms used by the control software in order to make the appropriate corrections.

Figure 2a presents a view of the developed instrument. The acquisition board is mounted on a cabinet that houses the signal conditioning circuits described before. The shunt used to measure the input current to the inverter is attached to the back of the cabinet (Figure 2b).

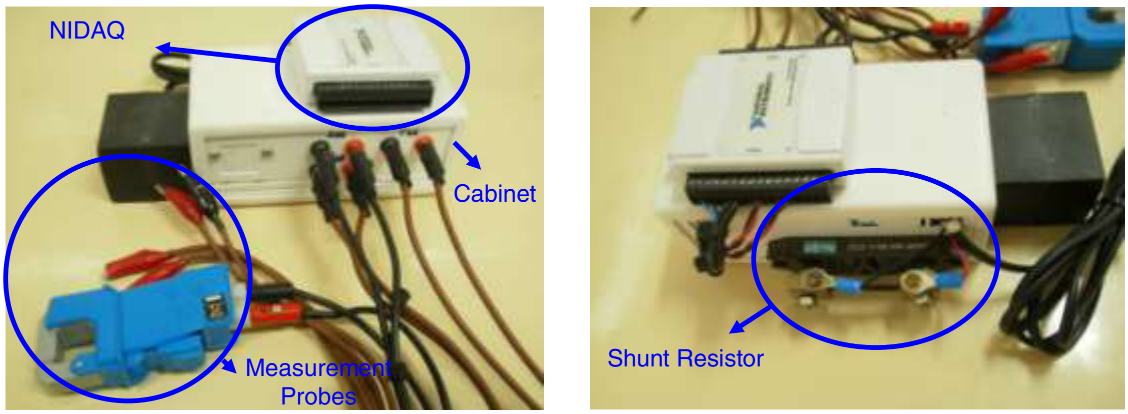

Fig. 2. (a) Cabinet containing the signal conditioning circuitry, acquisition board and voltage and current jack; (b) Shunt resistor used to sense the current at the input of the inverter.

The acquisition program, developed in Matlab R2010a programming environment, allows the adjustment of the configuration parameters required for the control of the acquisition module (sampling rate, acquisition time, number of samples, etc.). The software also processes the raw data by applying the corresponding correction factors for each channel, performs the digital filtering required to determine the average, fundamental, and higher harmonics components of the signal according to the parameter being measured and applies the corresponding equations for determining the calculated parameters, such as the power absorbed by the inverter, active and reactive power delivered to the grid, power factor, harmonic content of the output signals, total harmonic distortion, efficiency, etc.

3. Comparative test of the developed instrument

The European Standard EN 50530:2010 defines that the evaluation of the conversion efficiency of a inverter must be made for eight different load conditions (5, 10, 20, 25, 30, 50, 75, and 100% of the nominal DC power of the inverter) and three PV array curves (each one with its maximum power voltage V_{MP} corresponding to the nominal voltage and MPPT operation limit voltages). Moreover, according to the standard IEC 61683:2002, "Photovoltaic Systems - Power Conditioners - Procedure for measuring Efficiency", the uncertainty in the determination of the conversion efficiency of an inverter should remain below 1% of the full scale. For this reason and with the aim to limit instrumental errors, a comparison test was performed comparing the results obtained with the developed measuring system to the results gathered with the reference laboratory equipment.

The Solar Energy Laboratory at Universidade Federal do Rio Grande do Sul (LABSOL-UFRGS) has developed a test facility for the characterization of grid-tied inverters in accordance to the aforementioned standards. The key elements of the test bench are a Regatron TopCon Quadro TC.P.16.600.400.S 16 kW solar array simulator and a Fluke 434 power analyzer. Figure 3 shows a schematic diagram of such equipment and connections.

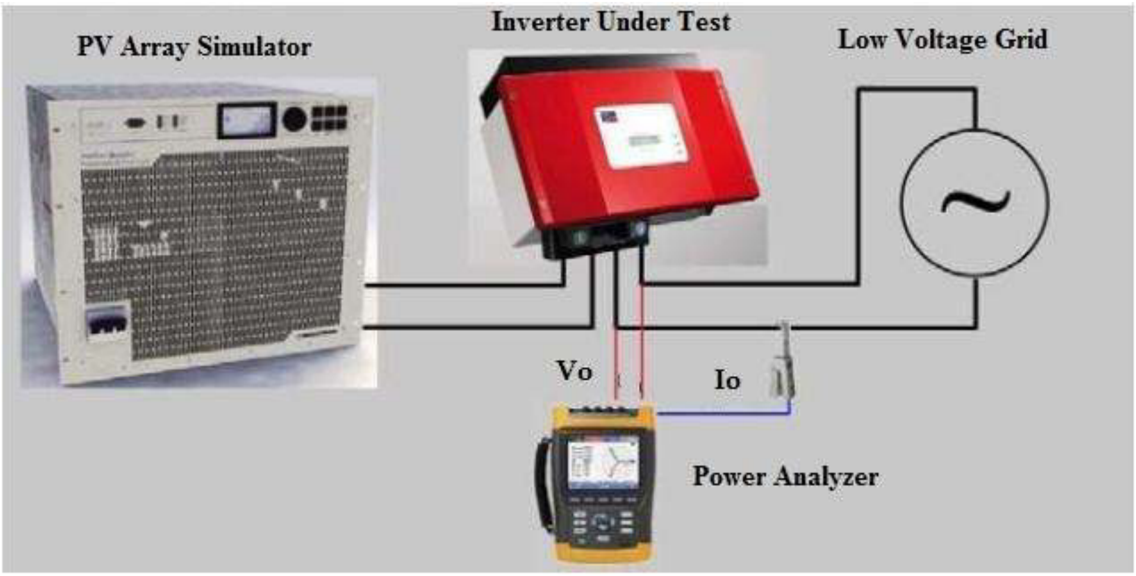

Fig. 3. Schematic diagram of the test bench developed at LABSOL-UFRGS. Source: Prieb (2011) [11].

The solar array simulator is basically a controlled power random function generator which, by menas of a suitable control software, is able to emulate in real time the electrical static and dynamic behavior of a physical photovoltaic array. The characteristics of the curve (maximum power, open circuit voltage, short circuit current, fill factor, etc.) can be easily modified by the software, providing versatility in testing without any dependence on climatic conditions. The solar array simulator has an internal acquisition system. This solar array simulator meets the conditions required by EN 50530:2010 for determining the conversion efficiency and maximum power point tracking efficiency of inverters.

According to the manufacturer, the equipment presents an accuracy of 0.1% FS (full scale) in current or voltage mode, and stability of 0.05% FS after 8 hours of operation. The resolution (for both programming and readback) is 0.025% FS for voltage and current and 0.1% FS for power.

The Fluke 434 power analyzer included in the LABSOL inverter test bench is used measure the AC signals at the output of the inverter under test, namely, voltage, current, power, harmonic content, power factor, etc. According to the manufacturer, this instrument provides an average accuracy of 0.5% [11].

The LABSOL inverter test facility allows the characterization of inverters both from the point of view of the conversion and MPPT efficiencies as well as the properties of the energy injected to the low-voltage grid. Therefore, it is a suitable tool to be contrasted to the characterization system developed at the GER. The LABSOL inverter test bench was used to determine the conversion efficiency curves of two grid-connected inverters (a FRONIUS IG20 and a SMA SUNNY BOY SB3800). The tests were repeated with same operating conditions with the signals measured by the equipment developed at GER, in order to compare the results of both systems.

According to the manufacturer, the rated AC power of the FRONIUS IG20 inverter is 1800 W. The maximum input voltage and current are 500 V and 14.3 A, respectively. This inverter is designed to be used with a line voltage of 230 V_{AC} (50/60 Hz). The maximum conversion efficiency, still according to the manufacturer, is 94.3%. Considering these characteristics, tests were performed for determining the conversion efficiency with the solar array simulator programmed with two *I-V* curves, with V_{MP} values of 170 V and 280 V. The rated AC power of the SMA SUNNY BOY SB3800 inverter is 3800 W. The maximum input voltage, current and power are 500 V, 20 A and 4040 W, respectively. The nominal line voltage is 230 V_{AC} (50/60 Hz), presenting a maximum conversion efficiency of 95.6%. For this particular inverter the tests were performed with *I-V* curves of three different V_{MP} values (215 V, 300 V and 400 V).

4. Results

Figure 4 shows the experimental results obtained for the efficiency of the inverter FRONIUS IG20 using the measurement systems developed at GER and LABSOL-UFRGS, with the solar array simulator programmed for *I-V* curves with (a) V_{MP} = 170 V and (b) V_{MP} = 280 V.

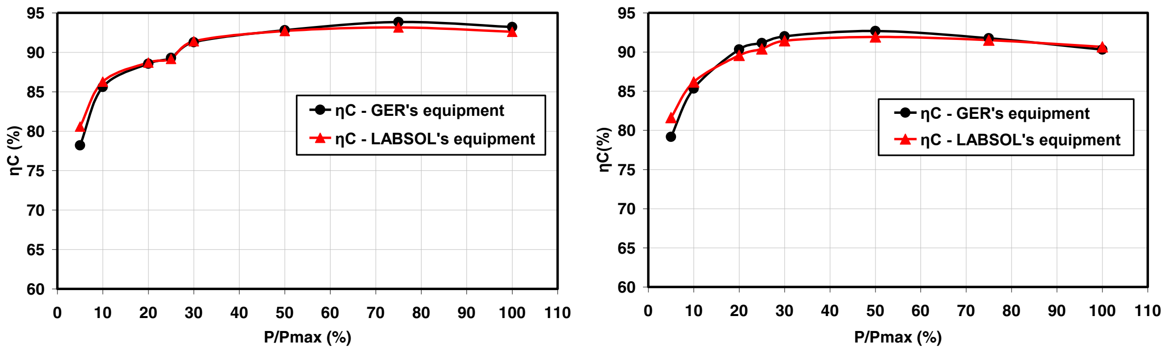

Fig. 4. (a) Conversion efficiency curves of the inverter FRONIUS IG20 obtained experimentally with the solar array simulator programmed for I-V curves with (a) V_{MP} = 170 V; (b) V_{MP} = 280 V.

As can be observed in Figure 4, the conversion efficiency curves of the FRONIUS IG20 inverter present a discontinuity for output levels between 20 and 30% of the nominal power, being this singularity more evident at the curve with higher voltage. According to the manufacturer, this line of FRONIUS inverters have a high frequency transformer with three taps which are automatically switched aiming to maximize the efficiency at partial loads, hence, the discontinuity is probably due to the switching between taps. The efficiency values obtained with the equipment developed at the GER for the referred power range (20 to 30%) agree with those obtained with the LABSOL system under both bias conditions (170 and 280 V) confirming the value of the instrument as a tool for the detection of such defects in the operation of grid-tied inverters.

It can also be observed that for loads above 10% of the nominal power, the conversion efficiencies measured with both systems are very similar, with differences below 1%. For lower loads the difference reaches 3% (Figure 5).

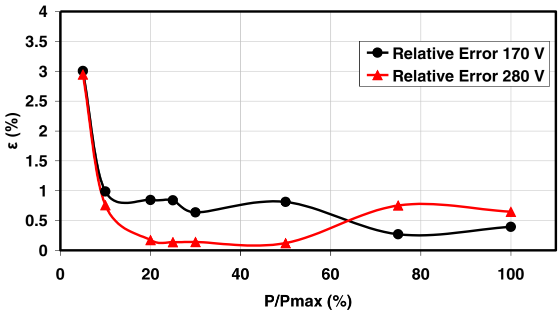

Fig. 5. Variation of the relative error in the determination of conversion efficiency of the FRONIUS IG20 inverter for two I-V curves with VMP = 170 V and 280 V.

Figures 6 and 7 present the conversion efficiency results of the inverter SMA SUNNY BOY SB3800 for three values of V_{MP} (215 V, 300 V and 400 V) and the corresponding experimental error.

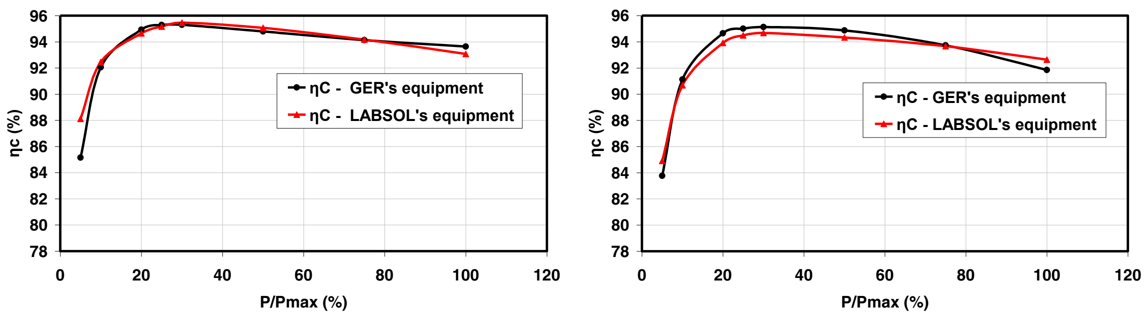

Fig. 6. Conversion efficiency curves of the inverter SMA SUNNY BOY SB3800 obtained experimentally with the solar array simulator programmed for I-V curves with (a) V_{MP} = 215 V; (b) V_{MP} = 300 V.

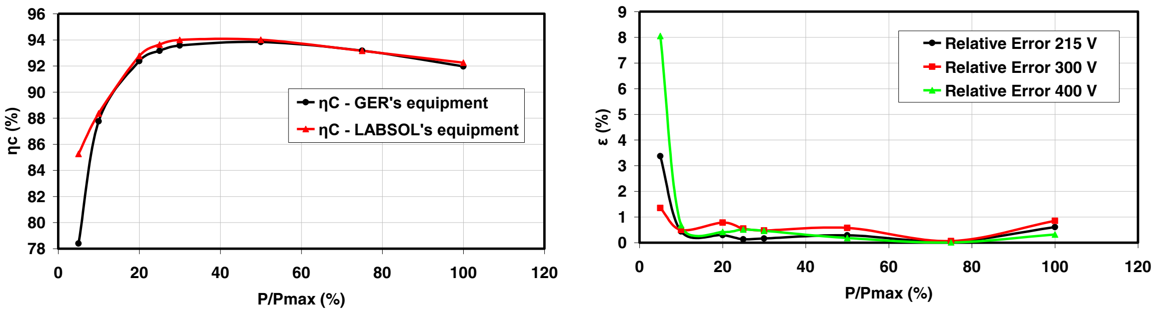

Fig. 7. (a) Conversion efficiency curves of the inverter SMA SUNNY BOY SB3800 obtained experimentally with the solar array simulator programmed for a I-V curve with VMP = 400 V; (b) variation of the relative error in the determination of conversion efficiency for three I-V curves with VMP = 215 V, 300 V and 400 V.

The relative high differences in the conversion efficiency results with the inverter at low power levels limit the application of the developed instrument to loadings ranging from 10% to 100% of the nominal power. Along this range the relative error is below 1% meeting the requirements of the relevant standards. Nevertheless, the maximum relative error in the evaluation of the efficiency corresponding to 5% of the rated load is less than 8% and is probably due to errors in determining the power factor of the current delivered to the grid, since most inverters present low power factor in this power range. This degradation in the power factor is due, mainly, to the effects of the unloaded line filters (mostly inductors) at the inverter output and also to the increased harmonic distortion and phase shift between the fundamental components of voltage and current at low levels of power. Rampinelli, 2010 [12] presents experimental results obtained from the testing of several inverters which corroborate this observation.

5. Conclusion

A measurement system to characterize grid-tied inverters in accordance with international standards was developed at GER-UNNE. This system is able to test inverters with nominal power up to 4.4 kW, although this limit can be expanded up to 10 kW by replacing the AC current probe. The comparison of the results obtained with the developed system to the results from a test facility at LABSOL-UFRGS indicated that the error in the efficiency evaluation remained below 1% for partial loads above 10% of the nominal power.

The continuation of this study includes the characterization of other six grid-tied inverters owned by LABSOL-UFRGS using the developed system, in order to increase the reliability of the measurements. Moreover, the instrument will be used to characterize inverters to be installed in different Argentinean universities within the framework of a FONARSEC project aimed at disseminating the use of grid-connected photovoltaic systems in Argentina.

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