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Assessment and mathematical modeling of energy quality parameters of grid connected photovoltaic inverters

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ABSTRACT

The insertion of photovoltaic solar energy has increased considerably over the past few years, with remarkable growth since 2005. It is essential that the electrical energy delivered by the photovoltaic system to the grid has an acceptable quality level. This paper presents test results of power factor and harmonic distortion content in grid connected inverters for photovoltaic systems. Several tests of ten commercially available inverter models from three different manufacturers were performed at the Laboratory of Solar Energy (Labsol) at the Federal University of Rio Grande do Sul (UFRGS), using a test bench with a power analyzer. The power factor and total harmonic distortion in current curves were mathematically modeled as a function of relative power in order to be used in computer simulation of photovoltaic systems. For power loads close to the nominal values, the harmonic content was found to be low and in accordance with the standard requirements. Nevertheless, at low loading levels the inverters may inject high levels of harmonics into the grid.

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1. Introduction

Grid connected photovoltaic systems (GCPVS) are the application of photovoltaic (PV) solar energy that have shown the most growth in the world. Since 1997, the amount of GCPVS power installed annually is greater than that all other terrestrial applications of PV technology combined [1]. Currently, the installation of grid connected systems represents nearly 100% of the market [1]. The PV installed capacity in 2013 was approximately 38 GW and the cumulative installed capacity in the world by the end of 2013 was almost 139 GW [2]. This data points to the success of photovoltaic solar energy in several countries.

Although Brazil has a great deal of potential solar energy, the insertion of PV technology is presently in the very initial stages and currently there are no support programs or feed in tariff

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specifically for PV systems. Support programs and governmental incentives create an economy of scale that consequently reduce costs and improve the market. Although incentive programs are only designed to be temporary, they are critical to the formation of a stable market [3,4]. The regulation of the electric sector plays an important role in assuring the availability of energy according to the country's future needs, encouraging its production considering the mid and long term needs as well as the necessity of offering cleaner energy sources.

A regulatory framework was released on April 17, 2012 when the Brazilian national electric regulatory agency (ANEEL) issued resolution no. 482 to regulate the installation of micro-generation (up to 100 kW) and mini-generation (from 100 kW up to 1 MW) systems connected to the grid as well as to establish net metering for these systems. In Brazil, public concessions of electric power plants are defined based on the result of public bidding. The first time this occurred specifically for photovoltaic energy plants was in October 2014, when approximately 889 MW of PV installations were granted to different parties.

The energy produced by photovoltaic systems is converted by electronic inverters and the energy quality is a constant issue for the electric authority. In this work, energy quality parameters of inverters up to 3800 W were analyzed.

2. The inverter and energy quality parameters

A grid connected photovoltaic system is basically constituted of a PV array, the inverter and other components needed to run the system. An inverter is the electronic device that converts DC power from the PV array to AC power that is injected into the grid with acceptable quality. The development of power electronic technology has provided a considerable increase in the efficiency and reliability of conversion and subsequently cost reduction. The inverters currently available in GCPVS feature important control functions such as maximum power point tracking, anti-islanding grid fault condition detection, energy measurement, etc. These inverters have different energy conversion circuits and topologies and they can have transformers for high or low frequencies, or they may not even have transformers at all. Each topology has its own characteristics, with its particular advantages and disadvantages. In general, transformerless inverters are more efficient but those with transformers have galvanic isolation from the DC to AC side [5–7].

Early grid connected PV systems were designed to work at low voltages at the DC side and the inverter had a low frequency transformer in the output. However, in addition to being heavy and expensive, the transformers impeded the ability of manufacturers to increase the inverter's efficiency. Now most of the photovoltaic plants work at higher voltages and transformerless inverters have gained market share and are more efficient than those with transformers. Since 2007, the Photon Laboratory has performed regular tests of inverter models from different manufacturers, finding transformerless inverters to be the most efficient [8]. Their use depends on the local grid regulations and can vary according to the country. In some places, for example, galvanic isolation between the DC and AC sides is mandatory.

The power injected into the grid by the PV system must comply with quality requirements in order to avoid major disturbances to the grid. A power quality problem can be defined as any event that manifests electrical disturbances in voltage, current or frequency causing damage or incorrect operation of equipment. Power quality is evaluated based on certain parameters set by the local electric authority. These parameters are usually low harmonic content, sinusoidal waveform with a frequency of 60 Hz (in Brazil) and power factor higher than a specified value. Failures or defects in the grid should not result in damage to the PV system and if this should occur, the equipment must ensure safe disconnection. Similarly, a failure or defect in the PV system should be identified by protective devices and should not affect other consumers of the electric system.

The impact on quality of electricity injected into the grid distribution is the subject of several studies [9–11]. They mainly explore the electrical characteristics of the inverters, such as harmonic distortion and power factor. For example, Infield and Simmons and Infield et al., analyze the energy quality injected into the grid by PV systems [12,13]. Kourtesi et al., evaluate strategies to reduce the harmonic content [14]. Caamaño-Martin et al., explore the impact of PV systems on the electrical grid [15] and Woyte et al., study the fluctuations in voltage that occur when PV systems inject power into the grid [16]. Several papers present studies and reviews of the state of the art of inverters used in grid connected photovoltaic systems [17,18]. Reviews of islanding detection techniques for renewable distributed generation systems are also the subject of many scientific studies [19–21].

2.1. Power factor

In purely resistive alternating current circuits, the voltage and current waveforms are in phase. However, in the presence of reactive loads such as inductors and capacitors, the energy storage in these loads results in a phase difference between the voltage and current waveforms. In switching or non-linear devices, the voltage and current waveforms are quite different and generate harmonic distortion. The power factor (PF) of an electrical system is defined as the ratio between the active power (P) and apparent power (S) as presented in Eq. (1).

$$PF = \frac{P}{S} = \frac{\frac{1}{T}\int V_i(t) \cdot I_i(t) \cdot dt}{V_{RMS} \cdot I_{RMS}} \quad (1)$$

where V_i and I_i are the voltage and current at time t, V_{RMS} and I_{RMS} are the root mean square of voltage and current and T is the period of the waveform which corresponds to the integration time used to calculate the power.

2.2. Total harmonic distortion

The total harmonic distortion in current (Eq. (2) left) is defined as the ratio of the RMS value of the harmonic components in the current and the RMS value of the fundamental component of the current. Similarly, the total harmonic distortion in voltage is defined as the ratio between the RMS value of the harmonic components in voltage and the RMS value of the fundamental component of the voltage (Eq. (2) right).

$$\mathrm{THD}_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \qquad \mathrm{THD}_V = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \quad (2)$$

where THD_I is the total harmonic distortion in current, I_n is the current component of the nth harmonic, I_1 is the fundamental component of current, THD_V is the total harmonic distortion in voltage, V_n is the component of the voltage of the nth harmonic and V_1 is the fundamental component of the voltage.

Power factor and harmonic distortion are topics of interest in several scientific studies [22,23]. Cardona and Carretero present a mathematical model to the total harmonic distortion in inverter current according to Eq. (3) [24].

$$\mathrm{THD}_I = A \cdot \left(\left(\frac{P_{CA}}{P_{NOM}} \right)^{-B} \right) \quad (3)$$

where A and B are fitting parameters of the mathematical model, P_{CA} is the output power of the inverter and P_{NOM} is the nominal inverter power.