

Provision of Ancillary Service in a Grid-Connected Photovoltaic Power System

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Abstract— In this paper, is studied the provision of ancillary service (AS) of harmonic compensation of a distributed generation (DG) connected in a distribution network is studied, aiming at the improvement of power quality (PQ). This compensation is performed by operating the three-phase inverter, whose dc bus is connected to the photovoltaic (PV) generator, acting as active power filter (APF) and DG. One of the advantages of the proposed strategy is that the compensation is performed without the need to extract the harmonic components present in the current, which reduces the computational effort. For implementation the measured grid current is used as control variable. The control is based on the power balance between the grid and the inverter, and is carried out in the synchronous reference frame. A perturb and observe (P&O) algorithm is used for maximum power tracking, along with a control algorithm for dc bus voltage. To validate the study, experimental results were obtained from an experimental setup in three different scenarios.

Keywords— ancillary services, distributed generation, harmonic compensation, power quality.

I. INTRODUCTION

With the increase in electricity consumption, and the concern over the preservation of the environment, the use of renewable sources of electricity, instead of the use of fossil fuels, has becoming increasingly important. Currently, there are 23.761 MW of power in Brazil associated with the photovoltaic plants. An addition of 2.980 GW in photovoltaic generation capacity is planned for the coming years [1]. The use of these renewable sources has been contributing to the growth of distributed generators connected to the grid. The distributed generation (DG) is usually operated in a grid-connected mode where the maximum available power is extracted from energy sources and transferred to the utility grid.

The introduction of DG in the distribution grid enables the provision of ancillary service (AS) to maintain the power quality (PQ) in the grid. The ASs are those services provided by generators used to support and ensure the power system in safe and reliable operation [2]. Usually, the AS in the power system is supplied by large conventional synchronous generators connected to the transmission system. This is done

by maintaining a certain level of active and reactive power availability for when there is a sudden change in demand.

Observing the increase in energy consumption by nonlinear loads, there is a growing concern about the grid's power quality. The presence of nonlinear loads connected to the point of common coupling (PCC) generates harmonic currents that, in contact with the line impedance, result in voltages with harmonic distortion, degrading the PQ for all consumers connected to the same grid. An alternative to minimize the PQ problems from DG, is using AS for harmonic compensation, so that the DG operates like an active power filter (APF).

A distributed generation system (DGS) with AS of harmonic compensation have been presented in [3–8]. The methods used in [3–5] required measurement of the load current and filter current. In [3,4] the harmonic detection is made in the synchronous reference frame (SRF) by the measurement of the load current. So the detected harmonic components are used to generate the reference current of the converter. In [5] the harmonic detection methods are the fast fourier transform (FFT) and third-order sinusoidal signal integrator (TOSSI), respectively.

In [6,7] it was necessary to measure the PCC voltage and the converter current. They performed the harmonic reference current generation by means of virtual impedance.

These methods have the disadvantage of using many sensors. In [9] was performed the harmonic compensation, as ancillary service, using the grid current measurement, in a single phase system.

In this paper is presented a three-phase DGS with AS connected to the grid for balanced systems, as can be seen in Fig. 1. The connection of the PV to the grid is carried out by means of a three-phase inverter to perform the following functions: injection of active power on the grid and simultaneously compensation of the harmonics. For generating the reference currents, it was used only the grid current (i_G). The control is based on the power balance between the grid and the inverter, and is based on abc-dq transformation. Compared to the papers aforementioned, the control strategy used in this paper requires less sensors and low computational complexity, since it does not need to extract harmonic components.

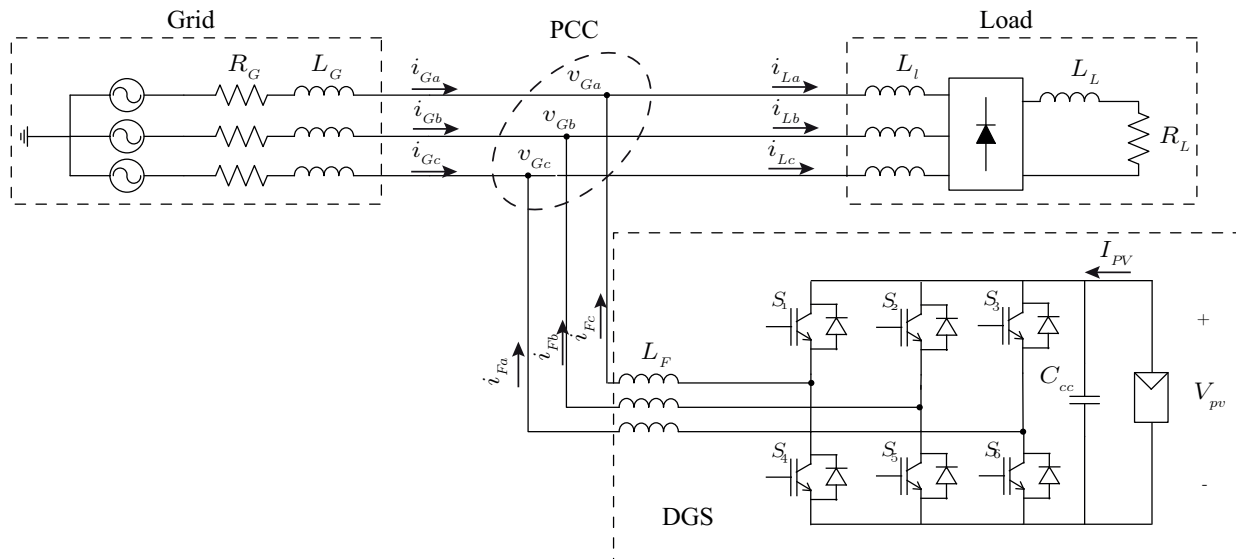


Fig. 1. Distributed Generation System (DGS) connected to the grid using a three-phase inverter.

II. DISTRIBUTED GENERATION SYSTEM STRUCTURE

In presence of nonlinear loads connected to the PCC, the grid current is affected by the harmonic distortion from the load nonlinearities. The regulation of the harmonic content can be accomplished by satisfying the standards constraints, such as IEEE-519 [10], which establishes limits for harmonic circulation in the power systems: total harmonic distortion (THD) of grid rated current lower than 5% for systems with voltage rated at between 120 and 69 kV. In this case, the DG can act as a shunt active filter injecting harmonics in opposite phase to perform the compensation. The complete system evaluated in this paper is shown in Fig. 1. A PV arrangement connected to the grid was used using a three-phase inverter. The nonlinear load, connected to the PCC consists of an uncontrolled rectifier feeding a RL load. The control is implemented based on V_{PV} , v_{Gabc} and i_{Gabc} . The voltage control is responsible to provide the fundamental reference for grid current, the description can be found in the next sections.

A. Voltage Control

In order to always operates at maximum power, a P&O algorithm was implemented to provide the reference for dc bus voltage [11]. The flowchart shown in Fig. 2 indicates how the dc-bus-voltage regulation is performed. The voltage on the dc bus is regulated depending on the power available in the PV array, i.e., when solar irradiance and panel temperature are favorable and the PV array produces sufficient power, the reference dc bus voltage (V_{dc}) is the P&O result, thus the panel voltage is (V_{PV}). On the other hand, in situations whether the PV is disconnected or the energy produced by the panel is insufficient, the algorithm sets the reference voltage to a minimum voltage requires to the dc bus.

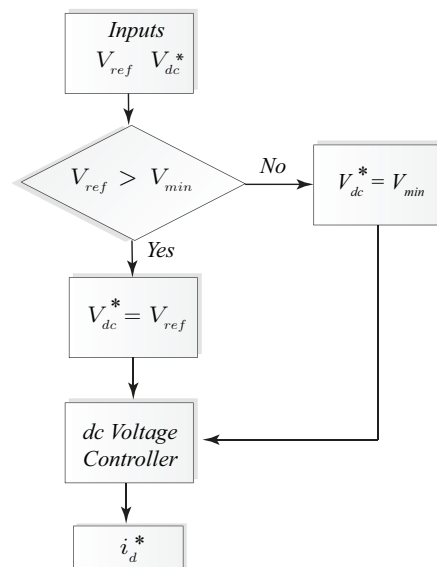


Fig. 2. DC bus voltage control.

B. Current Control

The current control is based on a method proposed by [12], in which the magnitude of the grid current depends on the power flow among the grid, the distributed generation system (DGS) and the load. If there is a power unbalance, as illustrated in Fig. 3, such as a transient caused by a load variation, the capacitor must provide the power difference between the grid and the load. For instance, considering that the power supplied by the grid is less than that load demanded, the current injected by the DGS will increase and the average voltage in the capacitor (dc bus). Whereas the dc bus is regulated, the reference grid current is increased, therefore increasing the power supplied by the grid until it stabilizes. On the other

hand, if the power supplied by the grid is higher than the load demand, the DGS current decreases, and the average voltage in the capacitor increases until the grid current minimizes to stabilize the power flow. In addition, when the power produced by the PV decreases, the fundamental component of the current injected by the distributed generator decreases; hence, the grid current must increase to counterbalance the power variation.

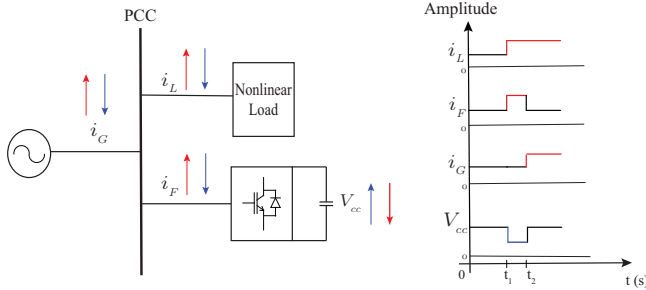


Fig. 3. Power Flow in the APF with method proposed by [12].

The current control diagram is presented in Fig. 4. Two of the three-phase grid currents (i_G) are measured by sensors, since the third can be obtained from the others. These currents are transformed to dq coordinates, so converting the current i_{Gabc} into i_{Gdq} as follows,

$$i_{Gdq} = \begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ \sin(\omega t) & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \times i_{Gabc} \quad (1)$$

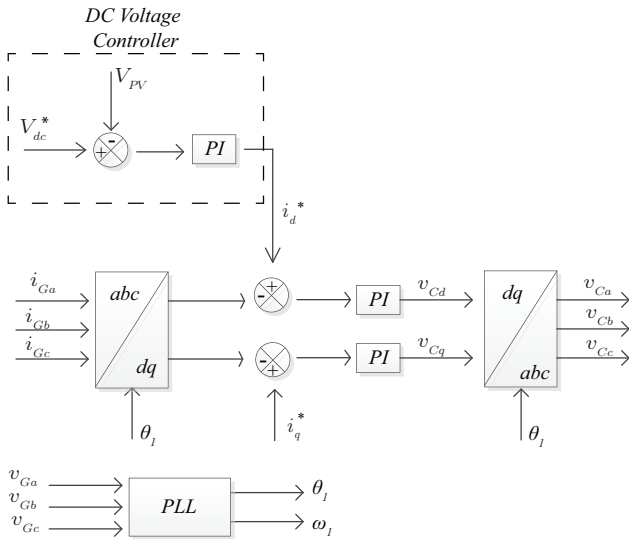


Fig. 4. Current control diagram.

The grid currents are the control variables, furthermore, the method used does not require the harmonics detection, and therefore, the computational effort is smaller compared to those presented in the introduction [3–8]. These currents are compared to the reference currents, provided by the dc voltage control, so that the error is the input of a proportional-integral

(PI) controller, whose output signals are the reference voltage for the pulse width modulation (PWM). It is worth to mention that the grid currents i_{Gabc} are, if properly controlled, sinusoidal for balanced and symmetrical systems. Therefore, they are controlled in the dq frame, thus allowing the use of PI controllers, in contrast to other strategies that control the current injected by the distributed generator [3–7]. Note that, the distributed generator currents have harmonics when AS is implemented.

An overview of the proposed control strategy is shown in Figure 5.

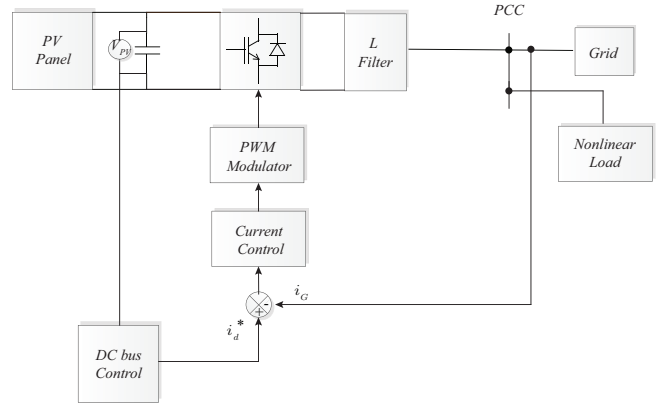


Fig. 5. Block diagram of the implemented control strategy.

III. RESULTS

Results were obtained experimentally according to the system presented in Fig. 1. An experimental setup is built in the laboratory to further verify the theoretical analysis the control strategy is implemented by using a digital signal processor (TMS320F28335 by Texas Instruments). The grid voltage is generated by a variable ac power source, and a three-phase diode rectifier feeding a RL load ($R_L = 17 \Omega$ and $L_L = 1 \text{ mH}$). is used as the nonlinear load.

The PV unit was represented by the E4360A modular solar array simulator (SAS) from Keysight. As E4360 provides a maximum voltage of 130 V, the grid voltage was set to 50 Vpk.

For the design of the coupling inductor, the method presented in [13] was used, in which the value of the inductance is given by the equation:

$$L = \frac{V_{PV}}{6 \times (N - 1) \times f_s \times \Delta I_r} = 2.8 \text{ mH} \quad (2)$$

where N corresponds to the number of inverter levels, f_s is the switching frequency of the inverter, V_{PV} is the voltage on the dc bus, and ΔI_r is the maximum current ripple.

The parameters used for the experimental results are shown in Table I.

TABLE I. EXPERIMENTAL PARAMETERS

System's Parameters		
Parameter	Value	Unit
Nominal grid voltage (v_G)	35	Vrms
Nominal frequency (f_r)	60	Hz
Inductance filter (L_f)	3	mH
DC bus capacitor (C_{dc})	2.2	mF
Switching frequency (f_s)	12	kHz
Nonlinear load	(r_L)	17 Ω
	(L_L)	1 mH

The DGS was tested in three scenarios:

1. DGS with active power injection with active power injection and AS of harmonic compensation in the PCC;
2. DGS with active power injection and AS of harmonic compensation in the PCC under irradiance variation;
3. DGS with active power injection and AS of harmonic compensation in the PCC under nonlinear load variation.

A. DGS with active power injection with active power injection and AS of harmonic compensation in the PCC

This Scenario represents the control of the GD unit connected to the PCC by an inverter as shown previously, in which it is desired to control the grid current to be sinusoidal.

For this scenario, the irradiance was adjusted to 1000 W/m², and in these conditions at the point of maximum power the SAS provided maximum voltage (V_{mpp}) of 120 V, the open circuit voltage of the SAS was adjusted to 130 V, the short circuit current to 2.5 A and the maximum current (I_{mpp}) of 1.8 A.

It was desired to maintain a voltage of 120 V on the dc bus of the inverter. Fig. 6 depicts the transient period of the PCC voltage (v_G), the current measured in the load (i_L), the compensated grid current (i_G) and the compensation current injected by the DGS (i_F), when the DGS starts to operate.

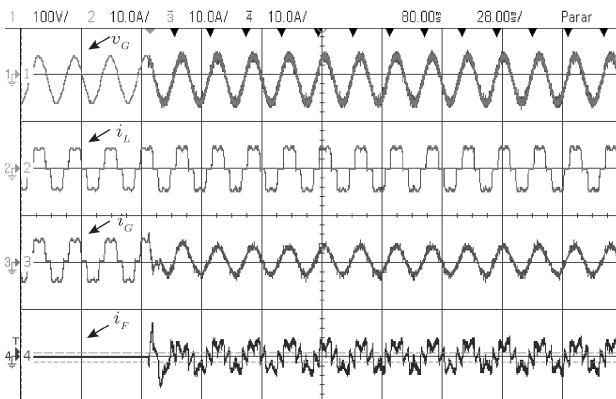


Fig. 6. Transient period: measured PCC Voltage (v_G) (100 V/div) and currents (i_L , i_G , i_F) (10 A/div, 10 A/div, 10 A/div) of the system.

As can be seen from Fig. 6, when the DGS starts to operate, the grid current becomes more sinusoidal. The injected current is composed of the active power from the DG and harmonic component, as shown in Fig. 7 with the spectrum of the steady state signals.

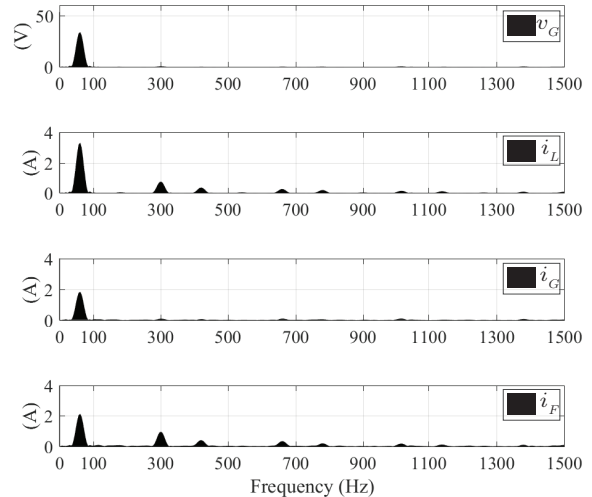


Fig. 7. Harmonic Spectrum: measured PCC Voltage (v_G) and currents (i_L , i_G , i_F) of the system.

From the harmonic spectrum is possible to note that the grid current is mainly composed by the fundamental frequency, thus observing the benefit of the supply of AS in the grid current.

B. DGS with active power injection and AS of harmonic compensation in the PCC under irradiance variation

Then, the effect of the irradiance variation in the system was analyzed, thus characterizing scenario 2.

The parameters used to perform the irradiance variation are shown in Table II. Initially the irradiance was 1000 W/m², then was reduced to 800 W/m², and finally to 500 W/m². By decreasing the irradiance, the injected active current decreases, so the grid current increases to compensate for the load, and the filter continues to provide active power and harmonics.

TABLE II. IRRADIANCE VARIATION

SAS parameters for different values of irradiance			
Parameter	$S = 1000W/m^2$	$S = 800 W/m^2$	$S = 500 W/m^2$
Open Circuit Voltage (V_{oc})	130 V	128,5 V	125,5 V
Short-Circuit Current (I_{sc})	2 A	1,6 A	1 A
Maximum Power Voltage (V_{mpp})	110 V	109,46 V	106,5 V
Maximum Power Current (I_{mpp})	1,8 A	1,5 A	0,95 A

Fig. 8 shows the panel voltage and current, respectively, under irradiance variation.

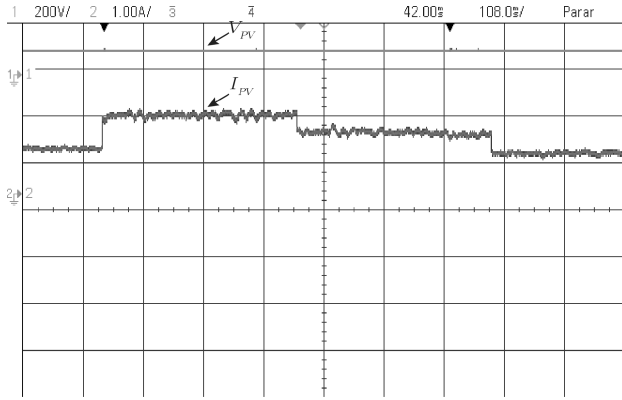


Fig. 8. Measured Panel Voltage (V_{PV}) (200 V/div) and current (I_{PV}) (1 A/div) of the system.

Observing the waveforms of Fig. 6 to 12, one can observe the operation of the control with the irradiance variation. By decreasing the irradiance, the current injected by the PV also decreases, so the grid increases its fundamental component to supply the current required by the load. Fig. 9 shows the waveforms of the voltage in the PCC and of the currents when the irradiance was 800 W/m^2 . In this case, the PV injects 1.5 A and the harmonics, with the grid supplying the remainder of the power demanded by the load.

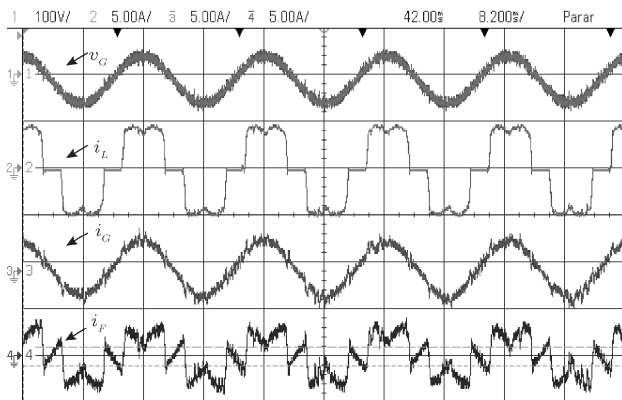


Fig. 9. Irradiance = 800 W/m^2 : measured PCC Voltage (v_G) (100 V/div) and currents (i_L , i_G , i_F) (5 A/div, 5 A/div, 5 A/div) of the system.

Even with the irradiance variation, the DGS continues to perform the harmonic compensation as well, the active power injection.

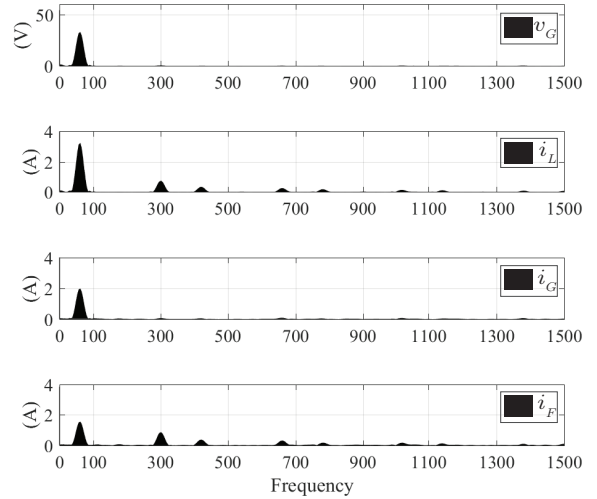


Fig. 10. Harmonic Spectrum - Irradiance = 800 W/m^2 : measured PCC Voltage (v_G) and currents (i_L , i_G , i_F) of the system.

By decreasing the irradiance even more, is noted the reduction of the PV current amplitude, and the growth of the grid current to provide power balancing, as shown in Fig. 11 and 12.

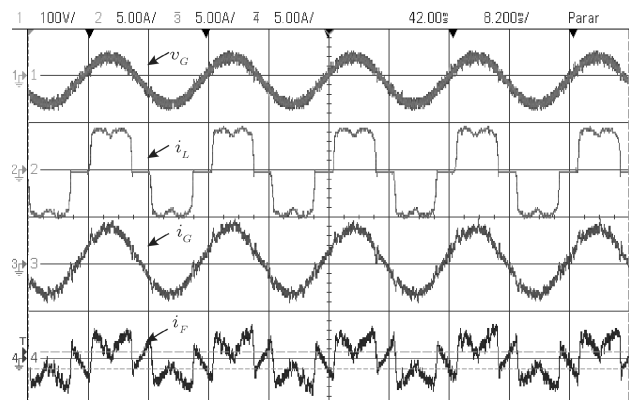


Fig. 11. Irradiance = 500 W/m^2 : measured PCC Voltage (v_G) (100 V/div) and currents (i_L , i_G , i_F) (5 A/div, 5 A/div, 5 A/div) of the system.

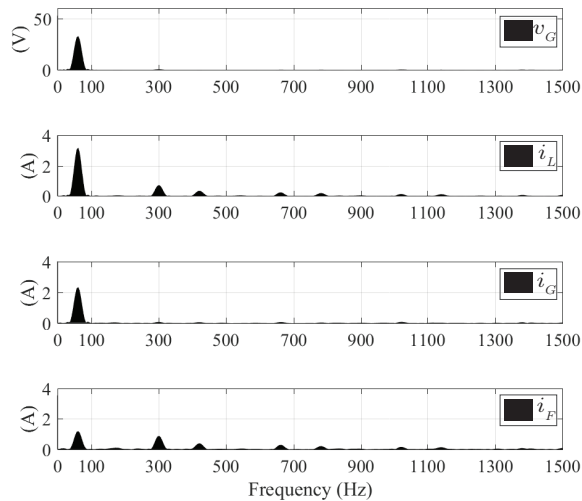


Fig. 12. Harmonic Spectrum - Irradiance = 500 W/m²: measured PCC Voltage (v_G) and currents (i_L , i_G , i_F) of the system.

C. DGS with active power injection and AS of harmonic compensation in the PCC under nonlinear load variation

To verify the robustness of the controller, a loading step of 40% has been inserted, as depicted in Fig. 13. As aforementioned, the control used in this paper is based on the power flow. Therefore, when the load step was applied there was an unbalance of transient power. The load and injected current increased, and until the mains current has increased to supply the power difference, the dc bus capacitor supplied the power difference.

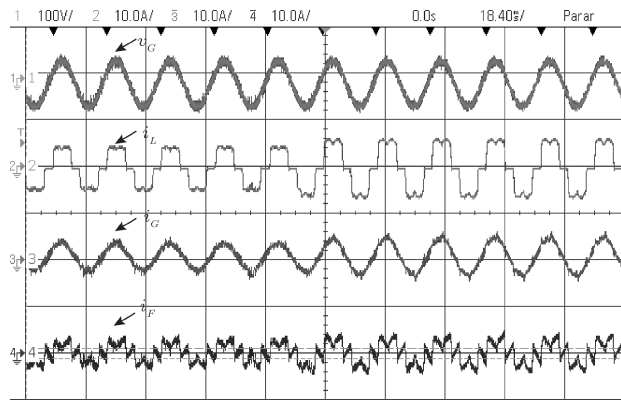


Fig. 13. Load variance: measured PCC Voltage (v_G) (100 V/div) and currents (i_G , i_L , i_F) (10 A/div, 10 A/div, 10 A/div) of the system.

In Fig. 14 are depicted the PCC voltage and currents in steady state after the load variation, in which the control maintains to provide the AS controlling the grid current to be sinusoidal.

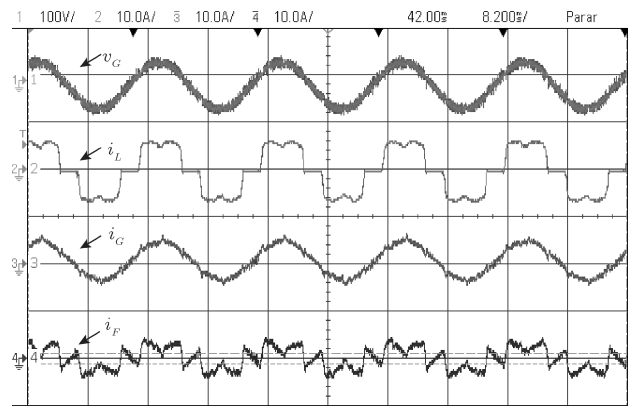


Fig. 14. Steady State – Load variance: measured PCC Voltage (v_G) (100 V/div) and currents (i_L , i_G , i_F) (10 A/div, 10 A/div, 10 A/div) of the system.

IV. CONCLUSION

In this paper a study was carried out on the supply of AS provided by distributed generators, specifically mitigation of harmonics from nonlinear loads at the coupling point. A distributed PV generator was used and the control strategy based on power flow was implemented.

For control of the system, the grid current was measured and used as control variable, thus reducing the amount of sensors used, without having to measure the load current, and using a conventional PI current controller. Despite the reduced number of current sensors, the quality of the grid current is significantly improved. The power control strategy implemented has as a positive feature the fact that it requires less computational effort, compared to other studies, as it doesn't need to perform the harmonics detection, it was efficient for the active power injection and the AS supply.

REFERENCES

- [1] ANEEL. Big - banco de informações de geração. <http://www2.aneel.gov.br/aplicacoes/capacidadebrasil/capacidadebrasil.cfm>, 2017. Accessed: 2017-10-20.
- [2] V. van Thong, J. Driesen and R. Belmans, "Using Distributed Generation to Support and Provide Ancillary Services for the Power System," *2007 International Conference on Clean Electrical Power*, Capri, 2007, pp. 159-163.
- [3] L. B. G. Campanhol, S. A. Oliveira da Silva, L. P. Sampaio and A. O. Azauri, "A grid-connected photovoltaic power system with active power injection, reactive power compensation and harmonic filtering," *2013 Brazilian Power Electronics Conference*, Gramado, 2013, pp. 642-649.
- [4] R. Belaidi, M. Fathi, M. M. Larafi, G. M. Kaci, R. Belaidi and A. Haddouche, "Power quality improvement based on shunt active power filter connected to a photovoltaic array," *2015 3rd International Renewable and Sustainable Energy Conference (IRSEC)*, Marrakech, 2015, pp. 1-6.
- [5] C. Khomsi, M. Bouzid and K. Jelassi, "A new efficient technique for disturbing current extraction to improve the grid current quality in a three-phase grid connected PV system supplying a non-linear load," *2016 7th International Conference on Sciences of Electronics, Technologies of Information and Telecommunications (SETIT)*, Hammamet, 2016, pp. 121-127..

- [6] R. Chilipi, N. Al Sayari, K. Al Hosani and A. R. Beig, "Control scheme for grid-tied distributed generation inverter under unbalanced and distorted utility conditions with power quality ancillary services," in *IET Renewable Power Generation*, vol. 10, no. 2, pp. 140-149, 2 2016.
- [7] Y. W. Li and J. He, "Distribution System Harmonic Compensation Methods: An Overview of DG-Interfacing Inverters," in *IEEE Industrial Electronics Magazine*, vol. 8, no. 4, pp. 18-31, Dec. 2014.
- [8] Thulluri Shiva and N Vijayakumar. Harmonic compensation of distribution generation using photovoltaic interfacing inverter. *IJSEAT*, 3(2):027–031, 2015.
- [9] Q. N. Trinh and H. H. Lee, "An Enhanced Grid Current Compensator for Grid-Connected Distributed Generation Under Nonlinear Loads and Grid Voltage Distortions," in *IEEE Transactions on Industrial Electronics*, vol. 61, no. 12, pp. 6528-6537, Dec. 2014.
- [10] IEEE recommended practice and requirements for harmonic control in electric power systems - redline. IEEE Std 519-2014 (Revision of IEEE Std 519-1992) - Redline, pages 1–213, June 2014.
- [11] R. Faranda and S. Leva. Energy comparison of mppt techniques for pv systems. *WSEAS transactions on power systems*, 3(6):446–455, 2008.
- [12] J. C. Wu and H. L. Jou, "Simplified control method for the single-phase active power filter," in *IEE Proceedings - Electric Power Applications*, vol. 143, no. 3, pp. 219-224, May 1996.
- [13] N. Y. Dai and M. C. Wong, "Design considerations of coupling inductance for active power filters," *2011 6th IEEE Conference on Industrial Electronics and Applications*, Beijing, 2011, pp. 1370-1375.