GRID-CONNECTED PHOTOVOLTAIC THREE-PHASE SYSTEM USING PARK TRANSFORMATION WITH ACTIVE AND REACTIVE POWER CONTROL AND INPUT VOLTAGE CLAMPED

Mateus F. Schonardie, Denizar C. Martins
UFSC - Federal University of Santa Catarina, INEP - Power Electronics Institute
P.O. Box 5119 88040-970 Florianópolis, SC, BRAZIL
E-mails: `mateus@inep.ufsc.br, denizar@inep.ufsc.br`

Abstract – **This work presents a model of the three-phase PWM inverter and a control strategy using Park transformation to be employed in a grid connected photovoltaic generation system. To control the power between the grid and photovoltaic system it is proposed the input voltage clamping of the inverter technique, where it is intended to achieve the maximum power point operation. The proposed system also operates as an active filter capable of compensate harmonic components and reactive power, generated by the other loads connected to the system. Following, simulation results and analysis are presented to validate the proposed methodology for grid connected photovoltaic generation system.**

Keywords - Photovoltaic Systems, DC-AC Converters, Maximum Power Point (MPP), Active Filters.

I. INTRODUCTION

The interest in the development of renewable energy sources generation systems, such as photovoltaic solar cells connected to the power grid, has increased in the last decades due to need of supplying the world increasing demand for electric power. Some works on distributed generation systems have been published with varied topologies and control strategies for three-phase systems [1, 2, 3, 4 5, 6].

There are some advantages that have been motivating grid-connected photovoltaic system applications, which are: the reduction in the costs of the PV panels [7]; capability of the system to supply AC loads, relieving the grid demand and making possible to send energy from the panels to the grid (distributed generation) and; its operation does not pollute the atmosphere (it does not harm any ecosystem) [8].

Recent researches developed in this area have shown another great advantage obtained with a grid-connected system, which is the possibility to accomplish a reactive power control originated from linear and non-linear loads also connected to the system [9]. So, these systems become more attractive because they accumulate two functions in the same system: energy generation and active filtering.

Following this research line, this work presents a three-phase PWM inverter modeling and a control strategy using Park transformation to be employed in a grid-connected photovoltaic generation system (Figure 1). In order to achieve the maximum power point (MPP) operation an input voltage clamping technique is proposed for the inverter. The proposed system also operates as an active filter capable of compensate harmonic components and reactive power, generated by the other loads connected to the system. To validate the proposed methodology some simulation results are presented.

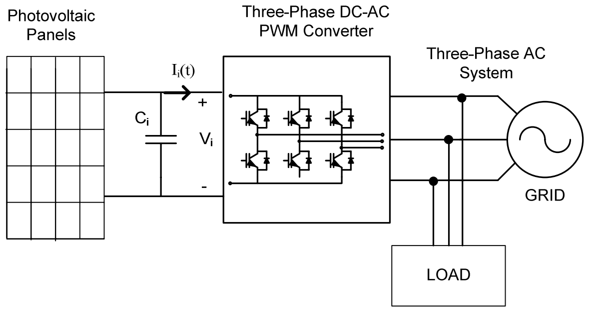

Fig. 1. Proposed Three-Phase Power Photovoltaic System.

II. MODELLING CONVERTER

This work presents a three-phase bi-directional DC-CA converter with PWM modulation using six power switches, shown in Fig. 2. The bi-directional characteristic of the converter allows it to operate with positive and negative values of active and it reactivate power (power flow from generator to load or load to generator), depending on the application. Thus, with an appropriate control of the power switches it is possible to control the active and reactivate power flow.

The converter modeling is relatively simple and is accomplished through Park Transformation. The model for the currents control is obtained considering the AC output, while the model to control the voltage across capacitor C_i is obtained considering the DC input.

To realize the modeling it can be used such line as phase variables. In this paper, the authors had chosen the line variables.

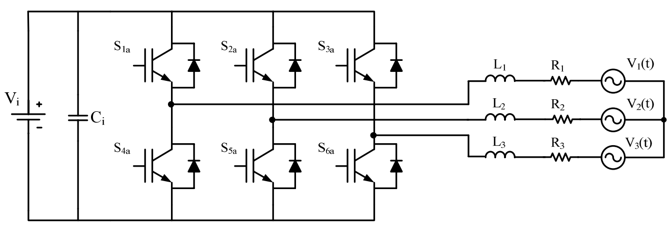

Fig. 2. Bi-directional DC-AC PWM Converter.

A. Current Control Modelling

Observing the circuit from the AC output, it is possible to make some initial considerations that result in a simplified circuit [10], shown in Fig. 3. The line voltages are presented in (1) considering $L_1=L_2=L_3=L$ and $R_1=R_2=R_3=R$. Applying Park and developing the equations, it is possible to find the differential equations that describe currents of axis *d* and *q* behavior, shown in (2).

$$\begin{cases} V_{12}(t) = L\cdot\dfrac{dI_{12}(t)}{dt} + D_{12}(t)\cdot V_i + R\cdot I_{12}(t) \\ V_{23}(t) = L\cdot\dfrac{dI_{23}(t)}{dt} + D_{23}(t)\cdot V_i + R\cdot I_{23}(t) \\ V_{31}(t) = L\cdot\dfrac{dI_{31}(t)}{dt} + D_{31}(t)\cdot V_i + R\cdot I_{31}(t) \end{cases} \quad (1)$$

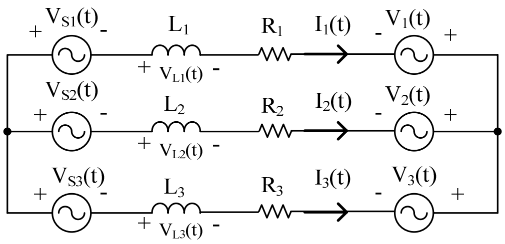

Fig. 3 – Simplified circuit to output AC

In (2), the direct axis current depends on the quadrature axis current and vice-versa. In order to decouple this dependence, a new duty cycle was defined and it is presented in (3).

$$\begin{cases} \dfrac{dI_d(t)}{dt} = \omega\cdot I_q(t) + \sqrt{\dfrac{3}{2}}\cdot\dfrac{V_p}{L} - \dfrac{V_i}{L}\cdot D_d(t) - \dfrac{R\cdot I_d}{L} \\ \dfrac{dI_q(t)}{dt} = -\omega\cdot I_d(t) - \dfrac{V_i}{L}\cdot D_q(t) - \dfrac{R\cdot I_q}{L} \end{cases} \quad (2)$$

$$\begin{cases} d'_d(t) = d_d(t) - \dfrac{\omega\cdot L}{V_i}\cdot i_q(t) \\ d'_q(t) = d_q(t) - \dfrac{\omega\cdot L}{V_i}\cdot i_d(t) \end{cases} \quad (3)$$

Developing appropriately this equations, it is possible to obtain the differential equations that show the behavior of currents of the axis *d* and *q* as functions of the duty cycles. So, the transfer functions used in the design of the current controllers are shown in (4).

$$\begin{cases} \dfrac{i_d(s)}{d'_d(s)} = -\dfrac{V_i}{s\cdot L + R} \\ \dfrac{i_q(s)}{d'_q(s)} = -\dfrac{V_i}{s\cdot L + R} \end{cases} \quad (4)$$

B. Voltage Control Modelling

The main purpose of this modelling is to accomplish the input voltage clamping $V_i(t)$, in order to control the power flow between the grid and the PV system. With the voltage clamping technique it is possible to accomplish the Maximum Power Point Tracking (MPPT) of the PV panels. There are many methods to implement a MPPT system in the literature [11],[12]. Amongst these methods, The Constant Voltage Method is accomplished by keeping the voltage in the PV terminals constant and close to the MPP [13], [14]. In Figure 4 an example of the current and voltage characteristics of a PV cell for different values of solar irradiation is presented. Observing the MPP points (*MPP Line*), it is possible to observe that the voltage values vary very little even when the intensity of the solar irradiation suffers great alterations. With the voltage clamped in a value “inside” of the *MPP Region*, when a variation of the solar irradiation happens, the current of PV cell will vary, however the output voltage of the PV will not be altered. This results in a control of the power flux of the PV cell to the grid.

Thus, it is necessary to obtain the transfer function of input voltage V_i as functions of axis *d* and *q* currents.

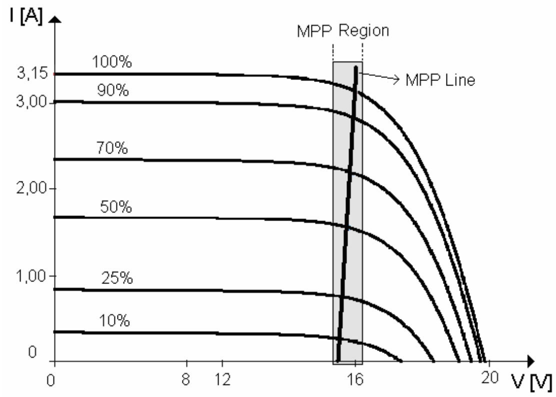

Fig. 4. Example of the current and voltage characteristics of a PV cell.

The equivalent circuit seen by the DC side is shown in Figure 5, where $I_i(t)$ represents the input inverter current (5), I(t) represent the current supplied by PV panels (6) and $I_{Ci}(t)$ represent the capacitor current (7). Developing and substituting appropriately this equations it is possible to obtain the transfer function between the voltage $v_i(s)$ and the input current of the inverter $i_i(s)$ according to (8).

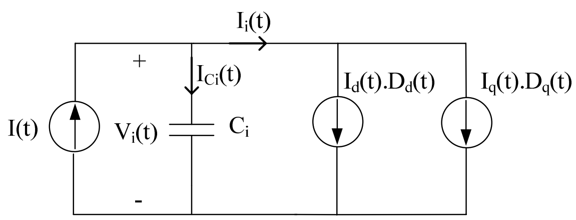

Fig. 5. Equivalent circuit seen by the DC side.

$$I_i(t) = I_d(t)\cdot D_d(t) + I_q(t)\cdot D_q(t) \quad (5)$$

$$I(t) = I_{Ci}(t) + I_i(t) \quad (6)$$

$$I_{Ci}(t) = C_i\cdot\frac{dV_i}{dt} \quad (7)$$

$$\frac{v_i(s)}{i_i(s)} = -\frac{1}{SC_i} \quad (8)$$

Developing and making some substitutions in (5) it is possible to obtain the desired modelling of the voltage v_i(s) as function of axis *d* and *q* currents are shown in (9).

$$\begin{cases} \dfrac{v_i(s)}{i_d(s)} = \dfrac{1}{s \cdot C_i} \cdot \left[\left(-\dfrac{\sqrt{2}}{\sqrt{3}} \dfrac{P \cdot L}{V_p \cdot V_i} \cdot s \right) - \dfrac{2 \cdot R \cdot P \cdot \sqrt{2}}{\sqrt{3} \cdot V_p \cdot V_i} + \dfrac{\sqrt{3}}{\sqrt{2}} \cdot \dfrac{V_p}{V_i} \right] \\ \dfrac{v_i(s)}{i_q(s)} = -\dfrac{\sqrt{2}}{\sqrt{3}} \cdot \dfrac{Q}{V_i \cdot V_p} \cdot \left[\dfrac{L \cdot s + 2 \cdot R}{s \cdot C_i} \right] \end{cases} \tag{9}$$

Where:

- P - Active Power
- Q - Reactive Power
- V_p - Voltage peak of the grid
- L, R - Equivalent Resistances and Inductances
- C_i - Input Capacitor
- V_i - Input Voltage
- i_d, i_q - Currents of the axis *d* and *q*.

III. IMPLEMENTATION OF THE CONTROL STRATEGY

The control strategy of the inverter output currents and input voltage, as well as the modulation used in this work are shown in Figure 6.

This strategy is implemented in the following way: the inverter output currents (I_1, I_2 e I_3) and the load currents (I_{1c}, I_{2c} e I_{3c}) are acquired through sensors. In the line currents it is applied Park Transformation to obtain the currents in the *dq0* way, according to Figure 7. The voltage in the capacitor C_i is compared with the reference voltage V_{iref} and the error signal enters in the voltage controller resulting in the signal I_{dref1}(t) (Figure 8). This signal I_{dref1}(t) is used as one of the references in the current control loop of the direct axis *d*, guaranteeing that voltage V_i(t) stays clamped at the desired value.

To control the currents of the axis *d*, the current I_d(t) and the reference currents I_{dref1}(t) and I_{dref2}(t) are used, according to Figure 9. The sign I_{dref2}(t) represents the load I_{dc}(t) alternate portion of the direct axis *d* current and it is obtained through a High-Pass Filter (Figure 10) [15]. This has negative sign so that the power flows in opposition to the load.

To control the currents of axis *q* (Figure 11), a reference signal I_{qc}(t) is used to compensate the reactive power caused by the non-linear load connected to the system. In the output of both controls (*d* and *q* axis) its necessary to accomplish a uncoupling in order to obtain the duty cycles d_d(t) as function of i_d(d) and d_q(t) as function of i_q(t).

The implementation of this control strategy requires a synchronism method with the grid, for example a PLL. In the pratical implementation a zero cross detector circuit will be used. This control strategy will be implemented with DSP (Digital Signal Processing).

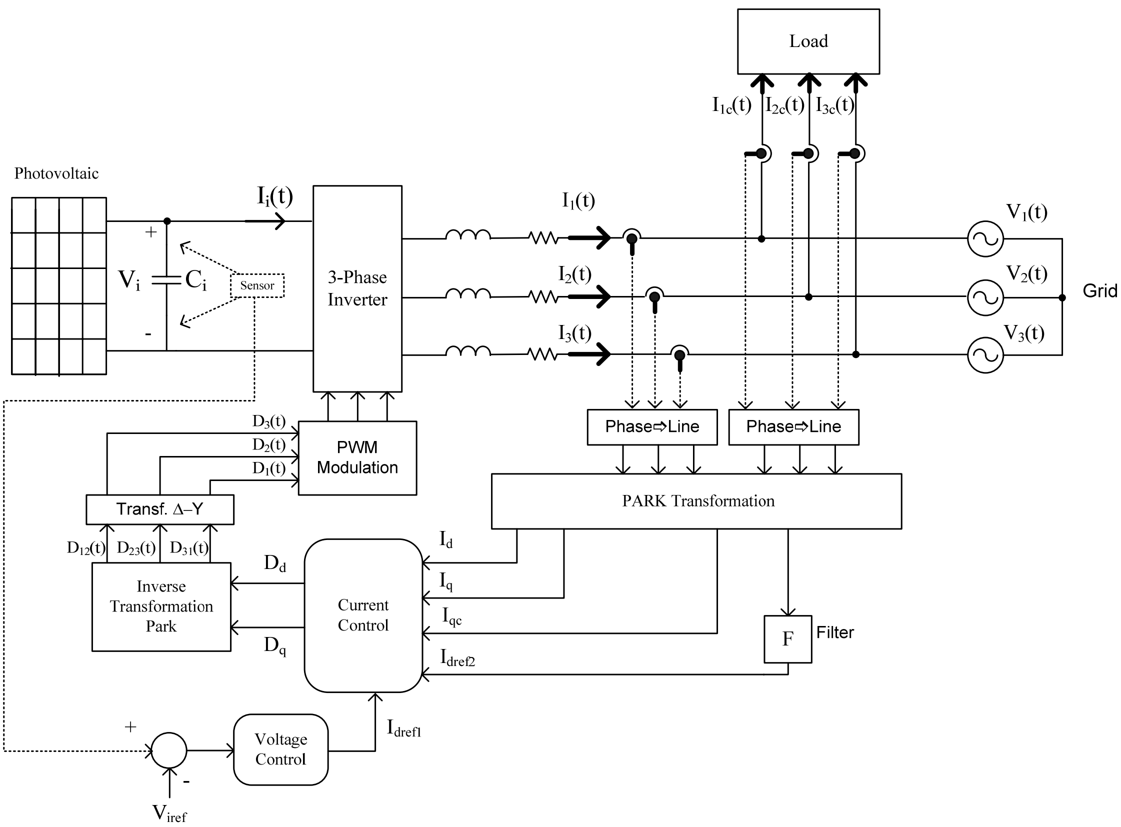

Fig. 6 – Diagram of the control system.

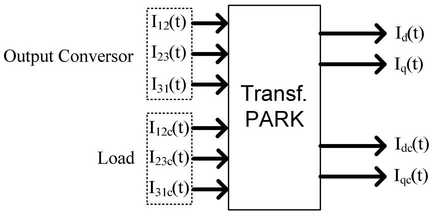

Fig. 7. Park Transformation of the line currents.

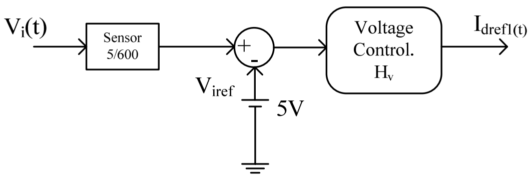

Fig. 8. Block Diagram of the voltage regulator.

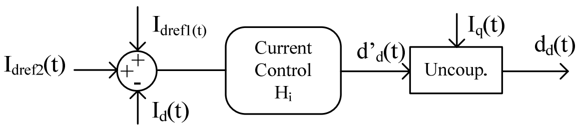

Fig. 9. Block Diagram of the current control in the d axis.

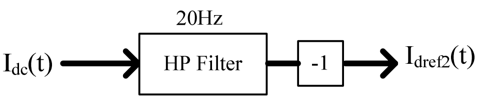

Fig. 10. $I_{dref2}(t)$ obtaining.

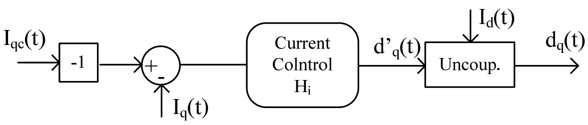

Fig. 11. Block Diagram of the current control in the axis q.

IV. SIMULATION RESULTS

Several numeric simulations were accomplished using the parameters shown in Table I for different situations of linear and non-linear load connected in the system. In this paper only the results considering non-linear loads connected to the system are presented. The non-linear load is a three-phase bridge rectifier with unbalanced input current and RC output.

The Figure 12 shows the grid currents (I_{1f}, I_{2f} and I_{3f}), load currents and input voltage $V_i(t)$ behavior, when a variation of the current supplied by the PV panels occurs at the instant t=150ms. Even with the non-linear load, the grid currents are sinusoidal and the voltage control maintain the desired level of 700V. Figure 13 shows the behavior of the current and voltage in Phase 1 of the grid, when an abrupt variation of the current supplied by PV panels occurs. In this test the energy supplied by the PV panels become null at the instant t=300ms and it returns to the nominal value at instant t=450ms. Even with this abrupt variation, the power factor in Phase 1 is very high in both cases; when there is solar irradiation (grid receiving energy) and in the periods when there is no energy supplied by the PV panels. In the absence of energy supplied by the PV panel, the converter only acts as an active filter. The inverter output current and the PV current are also shown in Figure 13. Figure 14 presents the three grid currents and the input voltage $V_i(t)$ behavior for this situation of abrupt variation.

TABLE I
Simulation parameters

Parameter	Description
P = 12 kVA	- Converter Power
V_i= 700 V	- Input Voltage (DC)
V_{out}= 220 V	- Output voltage rms (grid)
L = 1,92 mH	- Output inverter inductance
C_i= 2,7 mF	- Input Inverter capacitor
R = 0,57 Ω	- Output inverter equivalent resistor
f_r= 60 Hz	- Grid Frequency
f_s = 20 kHz	- Commutation Frequency

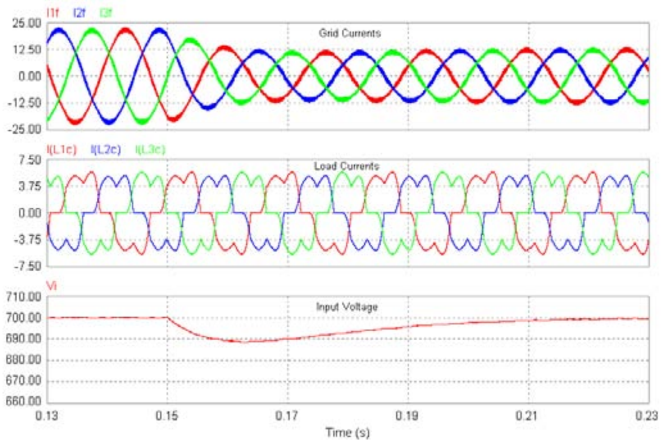

Fig. 12. Grid Currents, Load Currents and Input Voltage.

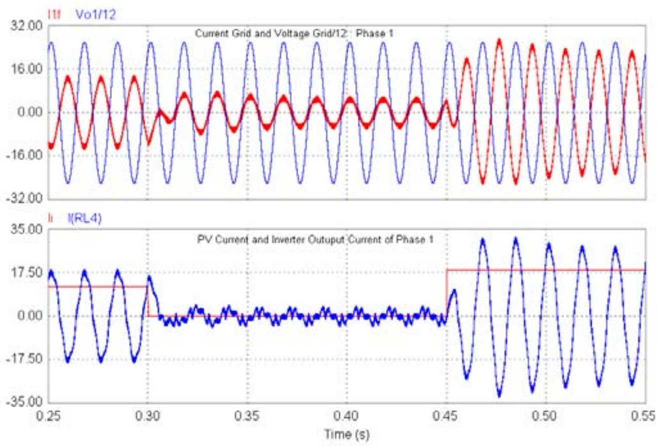

Fig. 13. Current and Voltage of Phase 1 – PV Current and Output Current Inverter of Phase 1.

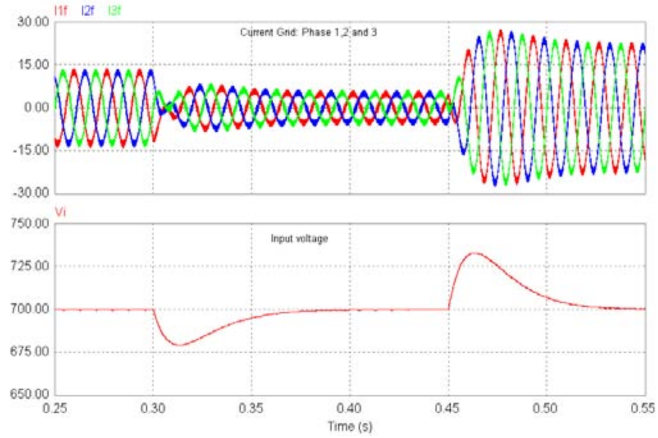

Fig. 14. Three grid currents and the input voltage

V. CONCLUSION

This work presented in a simple way the modelling and the control strategy of a three-phase PWM inverter to be employed in a grid connected photovoltaic generation system using Park transformation. The main focus of this work is to realize a design of a dual function system that would provide solar generation as well as harmonic and reactive compensation.

An input voltage clamping technique is used to assure the Maximum Power Point (MPP) of the PV panel. The developed system is also capable to operate as an active filter, compensating the unbalances of power and the reactive power generated by other loads connected to the system. It is important to observe that for both situations the Power Factor is always high and the currents present low harmonic distortion.

To prove the structure operation some simulation results were presented and they show the viability of the proposed model, as well as the control strategy used for PV systems. A laboratory prototype is being assembled.

ACKNOWLEDGEMENT

The authors would like to thank the CNPq -National Council for Scientific and Technological Development by the financial support.

REFERENCES

[1] O. Wasynczuk, N.A. Anwah. *Modeling and dynamic performance of a self-commutated photovoltaic inverter system;*Energy Conversion, IEEE Transactions on Volume 4, Issue 3, Sept. 1989 Page(s):322 – 328.

[2] W. Bohrer, M. Carpita, T. Ghiara, L. Puglisi. *A flexible control strategy to interface solar system with privileged load and utility line*. Electrotechnical Conference, 1989. Proceedings. 'Integrating Research, Industry and Education in Energy and communication Engineering', MELECON '89, Mediterranean 11-13 April 1989 Page(s):25 – 30.

[3] N. Mohan. *A novel approach to minimize line-current harmonics in interfacing renewable energy sources with 3-phase utility systems*. Applied Power Electronics Conference and Exposition, 1992. APEC '92. Conference Proceedings 1992. Seventh Annual 23-27 Feb. 1992 Page(s):852 – 858.

[4] S. Nonaka. *A novel three-phase sinusoidal PWM voltage source inverter and its application for photovoltaic power generation system.* Power Conversion Conference - Nagaoka 1997., Proceedings of theVolume 2, 3-6 Aug. 1997 Page(s):755 - 758 vol.2.

[5] I.H. Hwang, , K.S. Ahn, H.C. Lim, S.S. Kim, *Design, development and performance of a 50kW grid connected PV system with three phase current-controlled inverter.* Photovoltaic Specialists Conference, 2000. Conference Record of the Twenty-Eighth IEEE 15-22 Sept. 2000 Page(s):1664 – 1667.

[6] C. Cecati, A. Dell'Aquila, M. Liserre. *A novel three-phase single-stage distributed power inverter***.** Power Electronics, IEEE Transactions on Volume 19, Issue 5, Sept. 2004 Page(s):1226 – 1233.

[7] R. L. Carletti, L. C. G. Lopes, P. G. Barbosa, *Active & Reactive Powers Control Scheme for a Grid-Connected Photovoltaic Generation System Based on VSI With Selective Harmonic Elimination.* 8th Power Electronics Brazilian Conference, COBEP, Recife p. 129-134, 2005.

[8] F. A. Farret, M. G. Simões, *Integration of Alternative Sources of Energy.* "A Wiley-Interscience publication". IEEE, Copyright 2006 by John Wiley & Sons, Inc. 2006.

[9] M. C. Cavalcanti, G. M. S. Azevedo, K. C. Oliveira, B. A. Amaral, F. A. S. Neves, Z. D. Lins, *A Grid Connected Photovoltaic Generation System With Harmonic and Reactive Power Compensation*. 8th Power Electronics Brazilian Conference, COBEP, Recife p. 135-140, 2005.

[10] D. Borgonovo, *Modelling and Controlo d Three-Phase PWM Rectifier Using Park Transformation.* Florianópolis, 2001. Dissertation of Master in Electrical Engineering – INEP, UFSC.

[11] D. C. Martins, C. L. Weber, O. H. Gonçalves, A. S. Andrade, *PV Solar Energy System Distribution using MPP Technique*. VI INDUSCON – Conferência Internacional de Aplicações Industriais 2004.

[12] T. Esram, P.L. Chapman, *Comparison of photovoltaic array maximum power point tracking methods*, IEEE Transactions on Energy Conversion, in press.

[13] R. Demonti, Tese de Doutorado: *Processamento de Energia Elétrica Proveniente de Módulos Fotovoltaicos.* UFSC-INEP, 2003.

[14] M. J. Case, J. J. Schoeman, *A mínimum Component Photovoltaic Array Maximum Power Point Tracker.* European Space Power Conference, Granz, Austria p. 107-110, 1992.

[15] A. S. Morais, I. Barbi, *Power Redistributor Applied to Distribution Transformers of the Electrical Energy.* XVI Brazilian Automation Conference, CBA, Salvador p. 334-339, 2006.