European Association for the Development of Renewable Energies,
Environment and Power Quality (EA4EPQ)

*International Conference on Renewable Energies and Power Quality*
(ICREPQ'10)
Granada (Spain), 23th to 25th March, 2010

# Three Phase Grid Connected Photovoltaic System with Active and Reactive Power Control Using "Instantaneous Reactive Power Theory"

G. Adamidis[1], G. Tsengenes[1] and K. Kelesidis[1]

[1] Department of Electrical Engineering and Computer Engineering
Democritus University of Thrace, University Campus Kimmeria, 67100 Xanthi (Greece)
E-mail: **adamidis@ee.duth.gr**, **gt4773@ee.duth.gr**, **kkelesid@ee.duth.gr**

**Abstract.** In this paper, a photovoltaic (P/V) system, with maximum power point tracking (MPPT), connected to a three phase grid is presented. The connection of photovoltaic system on the grid takes place in one stage using voltage source inverter (VSI). For a better utilization of the photovoltaic system, the control strategy applied is based on p-q theory. According to this strategy during sunlight the system sends active power to the grid and at the same time compensates the reactive power of the load. In case there is no sunlight (during the night for instance), the inverter only compensates the reactive power of the load. The advantage of this strategy is the operation of the photovoltaic system the whole day. In this paper the p-q theory is proposed, which does not demand the use of PLL and introduces simple algebraic calculations.

## Key words

Grid-connected PV system, Maximum power point tracking, Instantaneous reactive power theory, Reactive power compensation, Power quality.

## 1. Introduction

Renewable energy sources are a very good solution in the global energy problem. Over the last decades the grid integration of renewable energy sources is carried out by power electronics [1]. The energy generated by photovoltaic systems constitutes a large part of the total amount of energy produced by renewable energy sources [2]. The output power of photovoltaic systems is significantly affected by weather conditions. Therefore, extracting maximum power from photovoltaic systems forms a major part of research activity. Several maximum power point tracking algorithms for photovoltaic systems have been developed [3]. These algorithms are applied in DC/DC converters [4] or in DC/AC inverters.

There have been many research efforts to improve the efficiency of photovoltaic system. These efforts aimed at supplying the grid with active and reactive power. In periods when there is no sunshine, the inverter supplies the network with reactive power only.

In tasks [5], [6], [7] a control algorithm is proposed based on synchronous rotating frame (SRF) for the adjustment of active and reactive power. The control of active and reactive power is based on the control of currents in the d-q rotating reference system.

In task [5] a DC\DC converter, two PI controllers and one PLL are used. However, this increases the cost and complexity of the system. In exercise [6] a DC-AC inverter and a PLL controller are used. Yet, the mathematical model for the control of reactive power is not clear. To extract reference current, passive filters are used, which introduce errors in the phase angle and in the width of the reference current [7].

This paper proposes the use of the theory of instantaneous reactive power (pq theory) [8] which controls the active and reactive power in the output of the inverter. The advantages of using this method are the absence of PLL and the application of simple algebraic calculations to raise speed of the system. Connection to the grid takes place in one stage. Also the method of incremental conductance (INC) is used to determine the maximum power point due to the simple mathematical analysis required [9].

In the remaining sections of this paper the proposed model of the photovoltaic array and the MPPT is described and the mathematical model of the inverter is presented. Finally, the simulation of the proposed system is carried out and the findings from the investigation are reported.

## 2. Description of the proposed system

The proposed system is shown in figure 1. For the analysis of this system the knowledge of mathematical models reflecting the electrical quantities in the output of the photovoltaic cell and photovoltaic panel [10] is required. These models are used by the MPPT algorithm for calculating the MPP.

https://doi.org/10.24084/repqj08.591

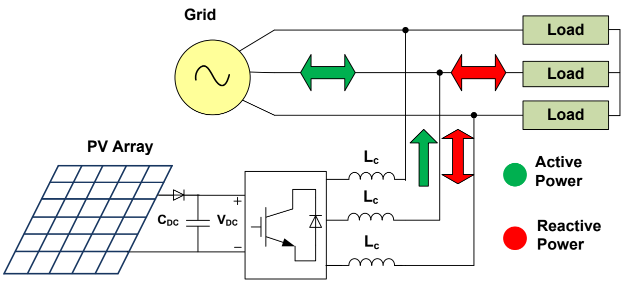


Fig. 1. Grid connected photovoltaic system.

### A. *Mathematical modeling of photovoltaic cell and photovoltaic panel*

A photovoltaic cell can be depicted as an equivalent circuit like the one in Figure 2.

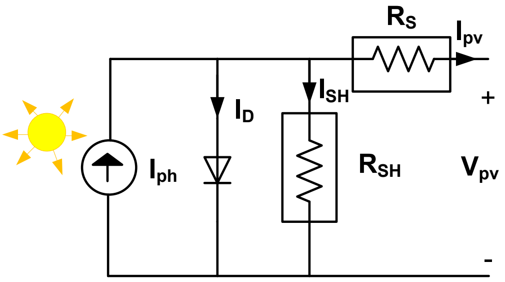


Fig. 2. Equivalent circuit of a photovoltaic cell.

The photo current $I_{ph}$ depends on solar radiation G and temperature T of the environment. In the photovoltaic system of this paper the temperature is equal to the nominal one, and the photo current $I_{ph}$ will depend only on solar radiation according to the equation (1):

$$I_{ph} = I_{ph(ref)} = \frac{G}{G_{ref}} I_{SC(ref)} \quad (1)$$

where $T_{ref}$ is the reference temperature, $G_{ref}$ is the nominal solar radiation and $I_{SC}$ is the short circuit current.

For a photovoltaic cell its output current is:

$$I_{pv} = I_{ph} - I_o\left[exp\left(\frac{V_{pv}+I_{ph}R_S}{V_T}\right)-1\right]-\left(\frac{V_{pv}+I_{ph}\cdot R_S}{R_{SH}}\right) \quad (2)$$

Where $\boldsymbol{I_{pv}}$ and $\boldsymbol{V_{pv}}$ are PV cells output current and voltage correspondingly, $\boldsymbol{I_o}$ is saturation current diode, $V_T$ is thermal voltage.

For s photovoltaic panel in series and p in parallel the equation (2) is expressed by the equation (3) the PVs output voltage by the equation (4)

$$I_{pv} = p\cdot I_{ph} - p\cdot I_O\cdot\left[exp\left(\frac{V_{pv}+I_{ph}\cdot\frac{s}{p}\cdot R_S}{s\cdot V_T}\right)-1\right] \quad (3)$$

and its output voltage is:

$$V_{PV} = s\cdot V_T\cdot log\left(\frac{p\cdot I_{ph}-I_{PV}}{p\cdot I_O}-1\right) - I_{ph}\cdot\frac{s}{p}\cdot R_S \quad (4)$$

The output power of PV cells depends on PVs output voltage $V_{pv}$ and PVs output current $I_{pv}$. Equation (5) gives the output power of PV cells:

$$P_{pv} = V_{pv}I_{pv} \quad (5)$$

### B. *Algorithm MPPT*

The MPPT algorithm which is used in this presentation is the incremental conductance (IC) algorithm. Conductance algorithm is able to calculate and not observe the direction towards which it should disrupt the operation point of P/V system in order to approach the MPP. Furthermore, it can determine when it has approached the MPP, thus avoiding oscillations around it. The block diagram of the IC algorithm is shown in figure 3.

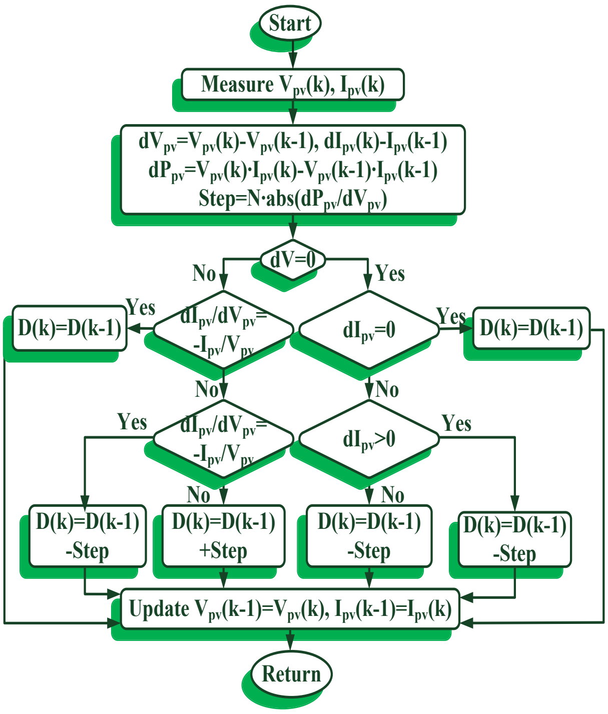


Fig. 3. Incremental conductance algorithm.

where D(k) and D(k-1) represent the state of the P/V panel in time k and time k-1 respectively.

## 3. Control strategy of grid connected P/V system.

For the control strategy of the grid connected P/V system the p-q theory is applied. To control the inverter's output current the hysteresis band current control technique is applied.

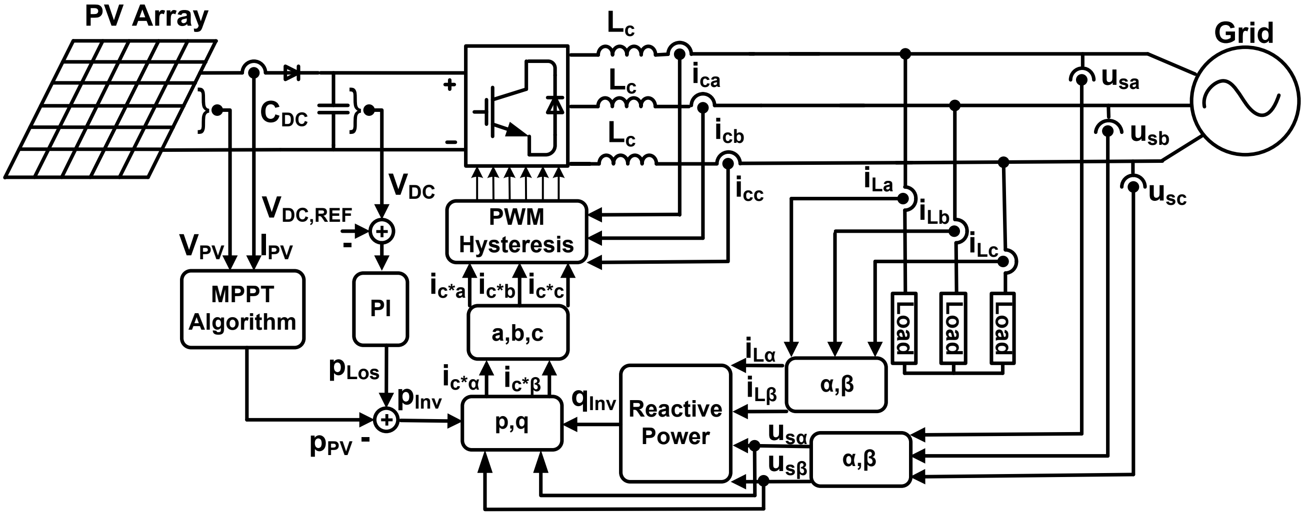


Fig. 4. Block diagram of the control strategy of P/V system.

The variables, which we measure, are the PV's output power $p_{PV}$, the capacitor's voltage $V_{DC}$, the mains' voltages $u_{sa}, u_{sb}, u_{sc}$ and the inverter's output currents $i_{ca}, i_{cb}, i_{cc}$, which are shown in figure 4. Active and reactive power control was based on the "instantaneous reactive power theorem". Figure 4 shows a block diagram of control and formation strategy of the proposed power system.

The advantage of this control method is that it introduces simple algebraic calculations and does not require the use of PLL to synchronize the PV system with the grid.

According to the "instantaneous reactive power theorem" mains voltages and load currents are transformed from a-b-c coordinates reference system to α-β coordinates reference system (Clark transformation). This transformation is shown in Figure 5.

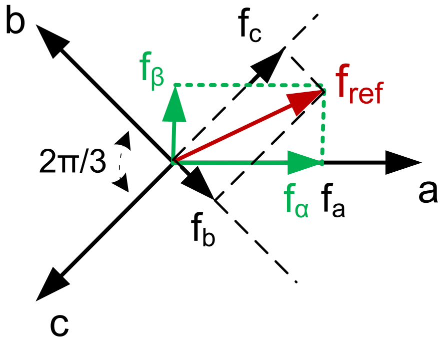


Fig.5. Transformation from a-b-c into $\alpha$-β coordinates system.

The mathematical relations of the load current and mains voltages in the two different coordinate systems are given by equations (6) and (7) respectively:

$$i_{L,\alpha\beta} = M i_{L,abc} \;,\; i_{L,abc} = M^{-1} i_{L,\alpha\beta} \tag{6}$$

$$u_{s,\alpha\beta} = M u_{s,abc} \;,\; u_{s,abc} = M^{-1} u_{s,\alpha\beta} \tag{7}$$

Where:
$i_{L,\alpha\beta} = [i_{L\alpha} \quad i_{L\beta}]^T, u_{s,\alpha\beta} = [u_{s\alpha} \quad u_{s\beta}]^T$,
$i_{L,abc} = [i_{La} \quad i_{Lb} \quad i_{Lc}]^T, u_{s,abc} = [u_{sa} \quad u_{sb} \quad u_{sc}]^T$ ,
$M$ is the matrix of Clark transformation and equals to:

$$M = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}, M^{-1} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$$

$M^{-1} = M^T$ because matrix M is an orthogonal matrix.

### *A. Reactive power control*

The p-q theory introduces a new variable, which is the instantaneous imaginary power q and corresponds to the instantaneous reactive power. The instantaneous reactive power with which the inverter feeds the load is given according to the p-q theory by the following equation:

$$q = u_{s\alpha} i_{L\beta} - u_{s\beta} i_{L\alpha} = [-u_{s\beta} \quad u_{s\alpha}] \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \tag{8}$$

### *B. Active power control*

Figure 9 shows the block diagram of active power control for the proposed photovoltaic system.

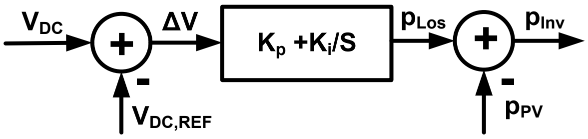


Fig. 6. Block diagram of inverter's active power control.

The MPPT algorithm gives the maximum power point, and hence the maximum power $p_{PV}$ of photovoltaic panel for a given radiation. Due to the switching operation of the voltage source inverter, some losses are caused in the circuit $p_{Los}$. According to the block diagram of Figure 6, the losses are covered by the solar energy when P/V system operates and supplies the grid with active power. During the period in which the photovoltaic system does not produce active power, then the losses $p_{Los}$ are covered by the inverter from the grid.

### *C. Reference Current Generation*

The p-q theory based on instantaneous active and reactive power, calculates the reference currents in α-β system according to the equation (9):

$$\begin{bmatrix} i_{c,\alpha}^{*} \\ i_{c,\beta}^{*} \end{bmatrix} = \frac{1}{\mathrm{u}_{s,\alpha}^{2}+\mathrm{u}_{s,\beta}^{2}} \cdot \begin{bmatrix} \mathrm{u}_{s,\alpha} & \mathrm{u}_{s,\beta} \\ \mathrm{u}_{s,\beta} & -\mathrm{u}_{s,\alpha} \end{bmatrix} \begin{bmatrix} -\mathrm{p}_{\mathrm{PV}} + -\mathrm{p}_{\mathrm{Los}} \\ -q \end{bmatrix} \quad (9)$$

Using the inverse transformation of equation (6) we calculate the reference currents in the a-b-c coordinates system according to the following equation:

$$\begin{bmatrix} i_{c,\alpha}^{*} \\ i_{c,b}^{*} \\ i_{c,c}^{*} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{c,\alpha}^{*} \\ i_{c,\beta}^{*} \end{bmatrix} \quad (10)$$

### *D.* Current Control

For the control of the output current of the inverter we will apply the hysteresis band current control technique, which is shown in figure 7 [11]. With this method we create a zone around the reference current trying to keep the inverter's output current within this zone. The advantages of hysteresis band control technique are its simple application, its very good dynamic behaviour and its fast response.

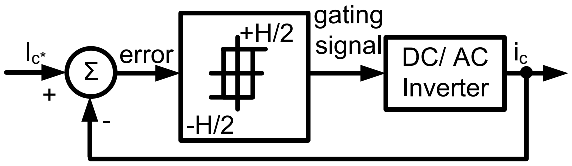


Fig. 7. Block diagram of hysteresis band current control technique.

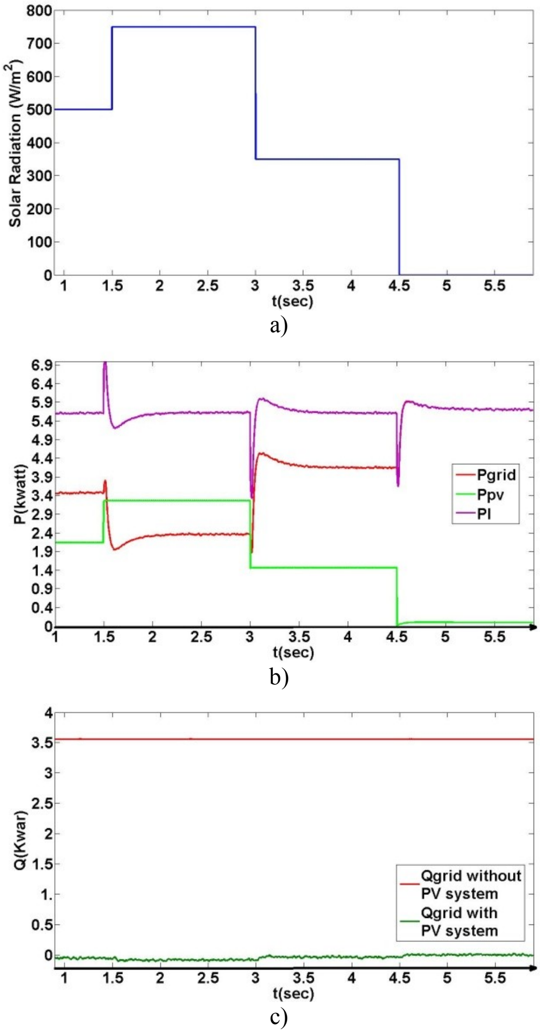
The hysteresis band current control defines the timing and duration of each pulse. The switching logic for phase "a" is summarized as follows:

- If the inverter's output current reaches the zone's upper limit then the upper switch is OFF and the lower switch is ON.
- If the inverter's output current reaches the zone's lower limit then the upper switch is ON and the lower switch is OFF.

The switching functions for phases "b" and "c" are determined similarly.

## 4. Simulation Results

We will simulate the proposed electrical power system of chapter 2. For the system's control we will apply the p-q theory. Figure 8.a shows the changes in solar radiation at specific times. It was felt that changes in solar radiation were instantaneous. Figure 8.b shows the corresponding modifications of the active power in both grid $P_{grid}$ and photovoltaic $P_{pv}$ to meet the real load power $P_l$. The sudden changes of $P_l$ were due to sudden changes of $P_{pv}$. In a real system changes in $P_{pv}$ are much slower; therefore changes in $P_l$ are much smoother. Also in Figure 8.c we observe the reactive power of the grid $Q_{grid.B}$ without the P/V system and the reactive power of the $Q_{grid.B}$ using the P/V system which acts as a reactive power compensator.



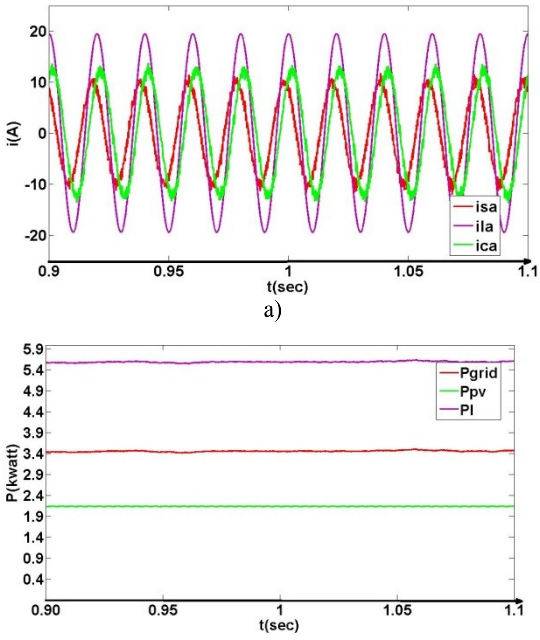
a)

b)

c)

Fig. 8. a) Solar radiation, b) active power of the grid, P/V system and load c) reactive power of the grid with and without the P/V system.

In this paper the behavior of the system for radiation $500\frac{w}{m^2}$ is investigated. Figure 9.a illustrates the phase a currents of the load $i_{La}$, the inverter $i_{ca}$, and the grid $i_{sa}$. From figure 9.a it is obvious that the load current is the sum of the inverter's current and the grid current. Figure 9.b shows active power of the load, of the grid and the P/V system. The grid and the P/V system meet the requirements of the load.

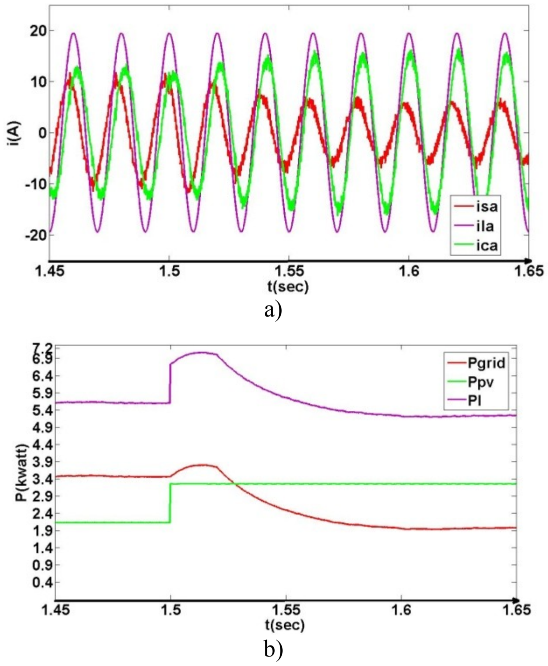


a)

b)

Fig. 9. a) the phase a currents of the load $i_{La}$, of the inverter $i_{ca}$ and the grid $i_{sa}$, b) active power of the load, of the P/V system and the grid.

Figure 10.a depicts the waveforms of phase a currents for the load $i_{La}$, the inverter $i_{ca}$, and the grid $i_{sa}$ in a transition, that is when the solar radiation is altered from $500\frac{w}{m^2}$ to $750\frac{w}{m^2}$. Figure 10.b shows the corresponding changes in real power of the load $P_l$, of the grid $P_{grid}$ and of the P/V system $P_{pv}$. A similar change exists in the current and the power when solar radiation is reduced.

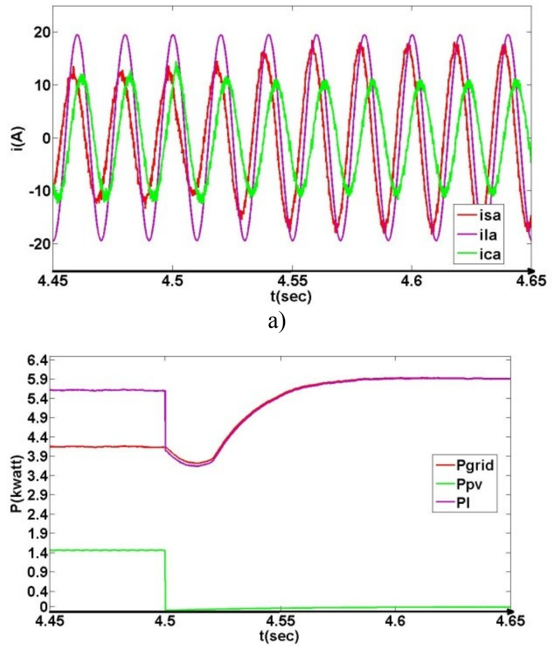


a)

b)

Fig. 10. a) the phase a currents of the load $i_{La}$, the inverter $i_{ca}$, and the grid $i_{sa}$, b) active power of the load, of the P/V system and the grid.

Figure 11 shows the transition when radiation becomes zero and the P/V system compensates only the reactive power of the load. Figure 11.a shows that the grid current increases while the current of the photovoltaic system is reduced. Figure 11.b shows the corresponding changes in real power of the load $P_l$, of the grid $P_{grid}$ and the F/V system $P_{pv}$. From a series of simulations on this operational state, it appears that the grid current is equal to the real load current, while the P/V system current is equal to the reactive load current.



a)

b)

Fig. 11. a) the phase a currents of the load $i_{La}$, the inverter $i_{ca}$, and the grid $i_{sa}$, b) active power of the load, of the P/V system and the grid.

The facts of the photovoltaic system and the grid which were simulated are given in table I and table II respectively.

Table I. – Parameters of P/V array.

| DESCRIPTION | PARAMETER |
|---|---|
| Number of parallel P/V panel | 2 |
| Number of P/V panel in series | 40 |
| Open circuit voltage | 20.1 V |
| Short circuit current | 3.45A |
| Reference solar radiation | 1000w/m$^2$ |
| Reference temperature | 24$^o$c |
| Saturation diode current | 4.05e-7 A |

Table II. – Parameters of electrical power system.

| DESCRIPTION | PARAMETER |
|---|---|
| Inductive Coupling | $L_C$ = 30.7 mH |
| DC Bus Capacitor | $C_{DC}$ = 1.3 mF |
| Load | $R_L$= 10 Ω , $L_L$=20mH |
| Grid | \|VS\| = 230V |
| Frequency | f = 50Hz |
| Induction of grid | $L_S$ = 0.15mH |

## 5. Conclusion

To increase the efficiency of photovoltaic systems in recent years their use has been studied in order to compensate reactive power. In this paper a simple and effective control method is proposed using the p-q theory so as the photovoltaic system to compensate the reactive power of the load throughout the day. In fact, the application of such a photovoltaic system in the household and in industry in order to compensate reactive power at night or other times of day when there is no sunshine, would greatly improve the power factor of the installation.

Future prospects of the present proposal include a more realistic modeling of photovoltaic cells and the modification of the control method so that the system works, even if the source voltage is not ideal and the load current contains harmonic components.

## References

[1] F. Iov, M. Ciobotaru, D. Sera, R. Teodorescu and F.Blaabjerg, "Power Electronics and Control of Renewable Energy Systems", PEMD 2007, Bangkok, pp. 6-28.

[2] Mohamed A. Eltawil, Zhengming Zhao, "Grid - connected photovoltaic power systems: Technical and potential problems-A review", ELSEVIER Renewable and Sustainable Energy Reviews 14 (2010), pp. 112-129.

[3] Roberto Faranda, Sonia Leva, "Energy comparison of MPPT techniques for PV Systems", WESAS TRANSACTION on POWER SYSTEMS, Issue 6, Volume 3, June 2008.

[4] Peftitsis D., Adamidis G., Bakas P., Balouktsis A., "Photovoltaic system MPPTracker investigation and implementation using DSP engine and buck – boost DC-DC converter" EPE-PEMC 2008.

[5] Huajum Yu, Junmin Pan, An Xiang, "A multi-function grid-connected PV system with reactive power compensation for the grid", ELSEVIER Solar Energy 79 (2005) 101-106.

[6] M.B. Bana Sharifian, Y. Mohamadrezapour, M. Hosseinpour and S. Torabzade, "Single-Stage Grid Connected Photovoltaic System with Reactive Power Control and Adaptive Predictive Current Controller", Journal of Applied Sciences, 2009 ISSN 1812-5654.

[7] Mateus F. Schonardie and Deniraz C. Martins, "Three-Phase Grid Connected Photovoltaic System With Active And Reactive Power Control Using dq0 Transformation", PESC 2008 Rhodes, pp. 1202-1207.

[8] Lazek S. Czarnecki, "Instantaneous Reactive Power p-q Theory and Power Properties of Three-Phase Systems", IEEE Transactions on Power Delivery Vol. 21 No. 1, January 2006.

[9] Fangrui Liu, Shanxu Duan, Fei Liu, Bangyin Liu and Yong Kang, "An Variable Step Size INC MPPT Method for PV Systems", IEEE Transactions on Industrial Electronics, Vol. 55, No. 7, July 2008.

[10] Tomas Skocil, Manuel Perez Donsion, "Mathematical Modeling and Simulation of Photovoltaic Array", ICREPQ 2008.

[11] Marian P. Kazmierkowski, Luigi malesani, "Current Control Techniques for Three-Phase Voltage-Sourece PWM Converters: A Survey, IEEE Transactions on Industrial Electronics Vol. 45 No. 5, October 1998.