MPP TRACKING METHOD FOR PV SYSTEMS, BASED ON A THREE POINTS PREDICTION ALGORITHM

Petru Lucian MILEA[1], Adrian ZAFIU[2], Marin DRĂGULINESCU[3], Orest OLTU[4]

Lucrarea prezintă o metodă de calcul computerizat pentru urmărirea punctului de putere maximă la sistemele fotovoltaice, cu ajutorul unui convertor în comutație. Metoda foloseşte ultimele trei valori determinate ale puterii, pentru ajustarea factorului de umplere al semnalului PWM ce controlează convertorul. Reglajele sunt făcute cu pas variabil pentru a minimiza timpul de căutare a MPP. Simulările au la bază modelele matematice ale panoului fotovoltaic şi convertorului în comutație, ce sunt de asemenea prezentate în lucrare. Metoda de urmărire a MPP se bazează pe un algoritm original ce utilizează o rutină de căutare binomiala. Rutina de căutare este finalizată în mai puțin de 15 paşi şi durează sub 50ms. Precizia urmăririi este mai mare de 99,98% pentru calculul pe 12 biți, superioară celor identificate în literatură de specialitate.

This paper present a computational MPP tracking method for photovoltaic systems, based on a boost converter. The method use the last three determined power values to adjust the duty cycle of the PWM signal which control the boost converter. The adjustments are made with a variable step in order to minimize the MPP searching time. The simulations are based on mathematical models of PV panel and boost converter, also presented in the paper. The MPP tracking method is based on an original algorithm which use a binomial search routine. The simulation based on the computed algorithm show very good perspectives. The searching routine is done in less than 15 steps and take less than 50ms. The tracking accuracy is more than 99.98%, for 12 bits computation, better than those found in literature.

Keywords: PV Systems, maximum power point, MPP tracking, boost converter

1. Introduction

The photovoltaic cell is a power source those parameters depends on some external factors like incident light angle, shading, ambient temperature etc. Some

[1] PhD student, Electronics Technology and Reliability Department, University POLITEHNICA of Bucharest, Romania, e-mail: lmilea@yahoo.com
[2] Assist., Department of Electronics and Computers, University of Pitesti, Romania, e-mail: adrian_zafiu@yahoo.com
[3] Lect., Electronics Technology and Reliability Department, POLITEHNICA University of Bucharest, Romania, e-mail: m.dragulinescu@gmail.com
[4] Prof., Electronics Technology and Reliability Department, POLITEHNICA University of Bucharest, Romania, e-mail: orest_oltu@yahoo.com

of these factors are unpredictable and, for this reason, we cannot predict the evolution of cell parameters.

The most known parameters of the photovoltaic cell are the open circuit voltage (V_{oc}) and short circuit current (I_{sc}). These values defines the points where the IV graph curve of the cell intersect the two axes (I and V). Between these point, the curve can have many shapes. Every point on the IV curve has specific values of V_i and I_i, defining the power as $P_i= V_i*I_i$. For a specific IV curve there are only one point corresponding to a maximum of power. This is named maximum power point or MPP. It is always good, for any power source, to supply electrical consumers at this point or near it.

There are some methods [1, 2, 3], in the scientific literature, to tune the electrical current to the value corresponding to MPP. This means, in other word, to adapt the impedance of the consumers to the optimal impedance for the power transfer. For this reason, the resulted circuits can be named as impedance adapters.

In our specific case, characterized by the near permanent modification of the *IV* curve, the MPP is also different almost at every moment. The new MPP has another maximum power and related *I* and *V*. For this reason, the power maximization of PV systems needs always dynamic impedance adaptor or MPP tracking devices. Many other unconventional power sources requires this kind of control [4] for optimal exploitation.

In this study, we propose a new computational method for dynamic MPP tracking of solar panels, based on pulse wave modulation control of a boost converter. Our study covers any potential kind of algorithm which has a quick response in solving nonlinear equations: genetic algorithms [5], adaptive algorithms [6], fuzzy algorithms [7] etc.

The tracking method must be able to find the MPP for an unknown type of solar panel, viewed as a black box.

Even if the irradiance and temperature values are unknown for each specific moment, the presented model will be able to maintain the desired output voltage, while tracking MPP, by using a secondary boost converter.

2. The mathematical model

In this section we present the used mathematical model of PV panel based on it’s elementary element: the photovoltaic cell. Specific values are computed from manufacturer supplied data [8]. In the model definition we use an incremental method in order to avoid standard solving of the complex equations of solar cell. The ideal model for the solar cell is the starting point of the study, completed in the next stage with other components. The most relevant characteristics of the photovoltaic cells model are used in the final application to dynamically track the MPP of a given solar cell with not known parameters.

2.1. Simplest model of the solar cell

The reference values of standard conditions are reference irradiance, named: G_{Ref} and reference temperature, named T_{Ref}. The performances of photovoltaic cells are evaluated under the following test conditions: the average solar spectrum (*AM 1.5*), the irradiance of *1000 W/m²* and the temperature of *25⁰C*. The parameters of solar cells are taken from suppliers specifications.

The photovoltaic cell light current I_L depend on both irradiance and temperature. The equation for I_L is:

$$I_L = \frac{G}{G_{Ref}}\left(I_{LRef} + \alpha\left(T + T_{Ref}\right)\right) \tag{1}$$

,where G is the actual irradiance, T is the actual temperature, I_{LRef} is the reference light current at reference conditions and α is the manufacturer supplied short-circuit temperature coefficient.

The ideal PV cell equivalent circuit contains a current source connected in parallel with a diode, as seen in figure 1.

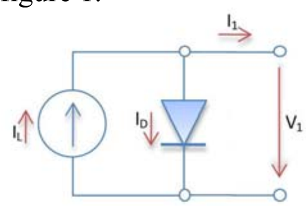

Fig. 1 First approximation equivalent circuit of a photovoltaic cell

The diode current I_D is given by Shockley equation:

$$I_D = I_0\left(e^{qV_1/akT} - 1\right) \tag{2}$$

where I_0 is the reverse saturation current, $q=1.602x10^{-19}$ *C* is the electron charge, a is the diode shape factor (between 1.0 and 2.0) and $k=1.381x10^{-23}$ *J/K* is Boltzmann constant.

By using V_T in the place of *akT/q*, the equation (2) becomes:

$$I_D = I_0\left(e^{V_1/V_T} - 1\right) \tag{3}$$

The reverse saturation current is:

$$I_0 = DT^3 e^{-q\varepsilon_G/akT} = DT^3 e^{-\varepsilon_G/V_T} \tag{4}$$

,where D is the diode diffusion factor and ε_G is the semiconductor material band gap energy. In our model we use the value for SI: $\varepsilon_G=1.12eV$

After some replacing and combining the equations (2) and (4), we obtain:

$$I_D = I_{0Ref}\left(\frac{T}{T_{Ref}}\right)^3 e^{\frac{\varepsilon_G}{V_T}\left(\frac{T}{T_{Ref}}-1\right)}\left(e^{\frac{V_1}{V_T}}-1\right) \tag{5}$$

The characteristic $I_1(V_1)$ of the primary equivalent cell it is expressed by equation (5), by considering given G and T.

The characteristic $I_1(V_1)$, drawn for $I_{LRef} = 5A$ and $I_{0Ref} = 10^{-6}A$, is shown in figure (2) and (3).

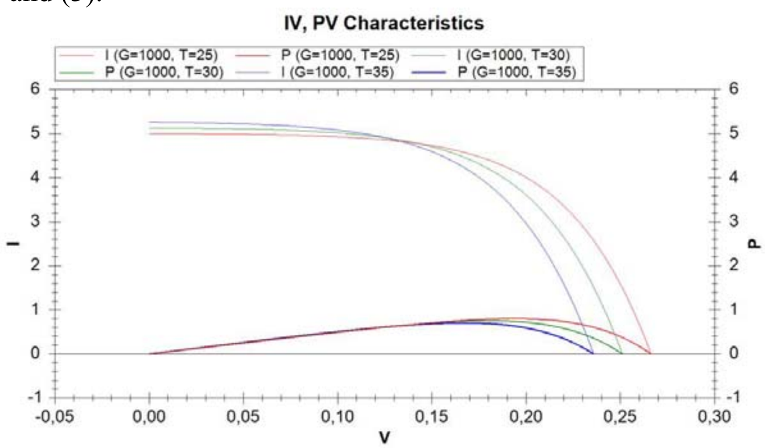

Fig. 2 $I_1(V_1)$ characteristics for T values: 25^0C, 30^0C, 35^0C and G=1000 W/m^2

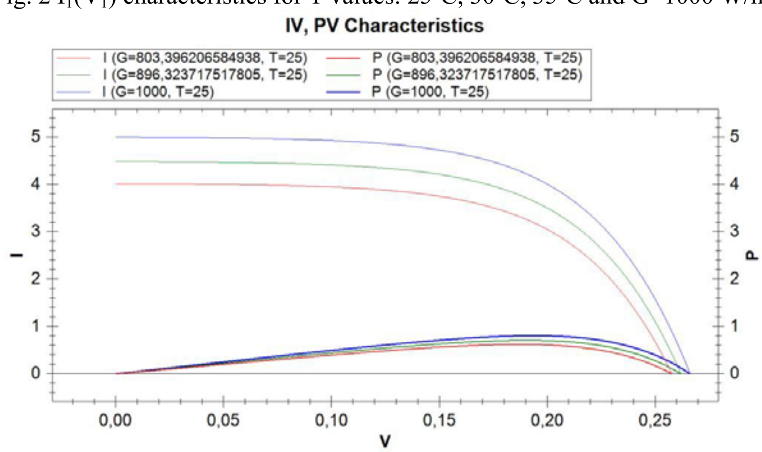

Fig. 3 $I_1(V_1)$ characteristics for G values: 803, 896, 1000 W/m^2 and T = 25^0C

The maximal power point (MPP) depends on the values of G and T. To compute the MPP we use the condition:

$$0 = \frac{dP_1}{dV_1} = \frac{dI_1V_1}{dV_1} = I_1 + V_1\frac{dI_1}{dV_1} \tag{6}$$

The relation between I_1 and V_1 is:

$$I_1 = I_L - I_D = I_L - I_0\left(e^{V_1/V_T} - 1\right) = \frac{G}{G_{ref}}\left(I_{Lref} + \alpha\left(T + T_{ref}\right)\right) - I_{0ref}\left(\frac{T}{T_{ref}}\right)^3 e^{\frac{\varepsilon_g}{V_T}\left(\frac{T}{T_{ref}}-1\right)}\left(e^{\frac{V_1}{V_T}} - 1\right) \quad (7)$$

,where I_D depends on V_1 and both I_L and I_D depends on G and T.
So, on given pair of G and T, the primary model can be considered a function with one input parameter, V_1.

From equation (7) we obtain:

$$\left.\frac{dI_1}{dV_1}\right|_{MPP} = -\frac{I_0}{V_T}e^{V_1/V_T} = -\frac{1}{R_{X1}} \quad (8)$$

,where we denote $R_{x1} = V_T/(I_0 e^{V_1/V_T})$ (9)

From equations (6) and (8) the equation for MPP become:

$$0 = I_1 - V_1 / R_{X1} \quad (10)$$

, which is a nonlinear implicit equation and has to be solved numerically.

2.2. The resistive influence on the PV cell equivalent circuit

The real solar cell contains dissipative elements which can be equalized with a shunt resistance R_P and a series resistance R_S, like in figure 2:

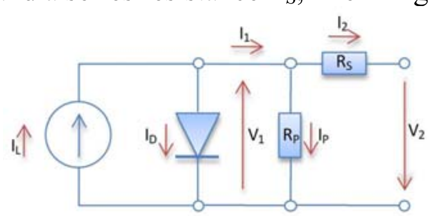

Fig. 4 Complete solar cell equivalent circuit

The new characteristic $I_2(V_2)$ is computed starting from the $I_1(V_1)$ characteristic. First we compute:

$$I_P = V_1 / R_P \quad (11)$$

From Kirchoff laws and equation (11) the equation for I_2 is determined:

$$I_2 = I_1 - I_P = I_1 - V_1 / R_P \quad (12)$$

By using (12) the equation for V_2 is immediate:

$$V_2 = V_1 - I_2 R_S = V_1\left(1 + \frac{R_S}{R_P}\right) - I_1 R_S \quad (13)$$

After some calculation and denoting:

$$R_{X2} = R_S + 1/(1/R_p + 1/R_{X1}) \quad (14)$$

,we obtain the following power characteristic:

$$\frac{dP_2}{dV_2} = I_2 - V_2 / R_{X2} \tag{15}$$

The influence of resistors R_S and R_P is shown in figure 5:

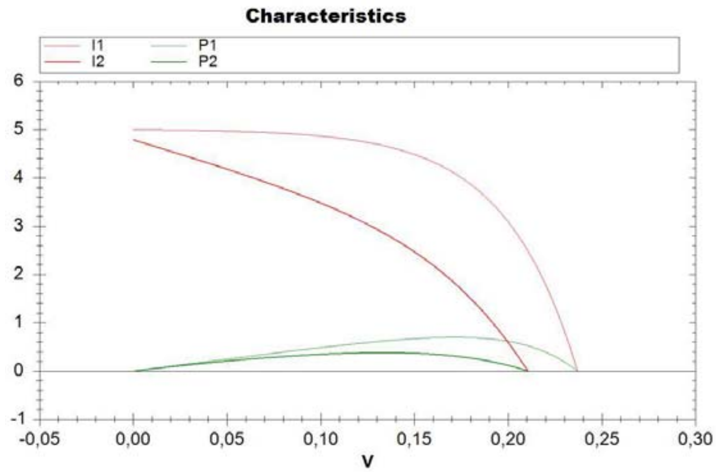

Fig. 5 The influence of resistors R_S and R_P

For the MPP the equation is (from 15):

$$\frac{dP_2}{dV_2} = 0 \Rightarrow I_2 = V_2 / R_{X2} \tag{16}$$

As we can see from figure 5, the general allure of the current and power characteristics are not changed by taking into consideration the resistive effects from inside the sollar cell.

2.3. The PV panel equivalent circuit

A PV panel is defined as an array of solar cells usually encapsulated, for protection. The cell are connected in series to obtain the desired output voltage and then in parallel to obtain desired output current.

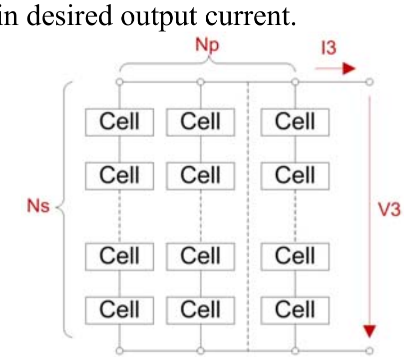

Fig. 6 Photovoltaic module

In figure 6 is presented a scematic of a PV panel. N_S is the number of rows (series) and N_P is the number of columns (parallel).

For the module, we consider the global equation:

$$I_3 = I_L^M - I_0^M\left(e^{(V_3+I_3R_S^M)/(NsV_T)} - 1\right) - \frac{V_3 + I_3R_S^M}{R_P^M} \quad (17)$$

where the currents and resistance values are multiplied by N_S and N_P.

The condition of MPP becomes:

$$0 = \frac{dP_3}{dV_3} = I_3 - \frac{V_3}{R_{X3}} \quad (18)$$

, where: $$R_{X3} = R_{X2}N_S / N_P \quad (19)$$

The characteristic allure for P_3 and I_3 are identical with that of P_2 and I_2, P_1 and I_1. Only the values on the axes are multiplied by N_S and N_P.

3. Boost control circuit

To control the current taped from the PV panel we use a boost circuit [9], which schematic is presented in figure 7:

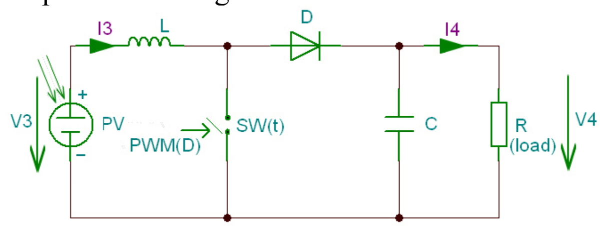

Fig. 7 The general schematic of a boost circuit

The ideal relations between input values and load parameter are influenced by the fill factor D of the boost circuit.

The equations are:

$$V_4 = V_3/(1-D) \quad (20)$$

$$I_4 = I_3(1-D) \quad (21)$$

Because of resistive loses inside of the components, we need to introduce the efficiency, η, which defines the power transfer:

$$P_4 = \eta P_3 \quad (22)$$

Considering that the resistor R of the load circuit has a fixe value, the report between V_3 and I_3 is adjusted by using the variable D:

$$I_3 = \frac{V_3}{R(1-D)^2} \quad (23)$$

The equation (23) represents the dependency of the the equivalent impedance (V_3/I_3) of the boost circuit, by the duty cycle D of the control PWM signal.

From the condition at MPP (18) and (23), we obtain:

$$R_{X3} = R(1-D)^2 \quad (24)$$

The equation (24) reveals that the power transfer is maxim when the load impedance becomes equal with the internal dynamic impedance of the PV panel (power source). This is a well known law in power transfer and it applies to the PV panels too.

4. Computing MPP with a three dynamic step method

The proposed method consists in the adjustment of the pulse width which control the boost converter, with dynamic step, based on the last three previous obtained successive (*I,V*) pairs. By comparing the values of that pairs, the control algorythm decides the step and direction of the next adjustment.

We consider that the first points are equidistant. Value *D* corresponds to the middle point. First point corresponds to value *D*-Δ and last point corresponds to the value *D*+Δ. At each step, the values *D* and Δ are adjusted.

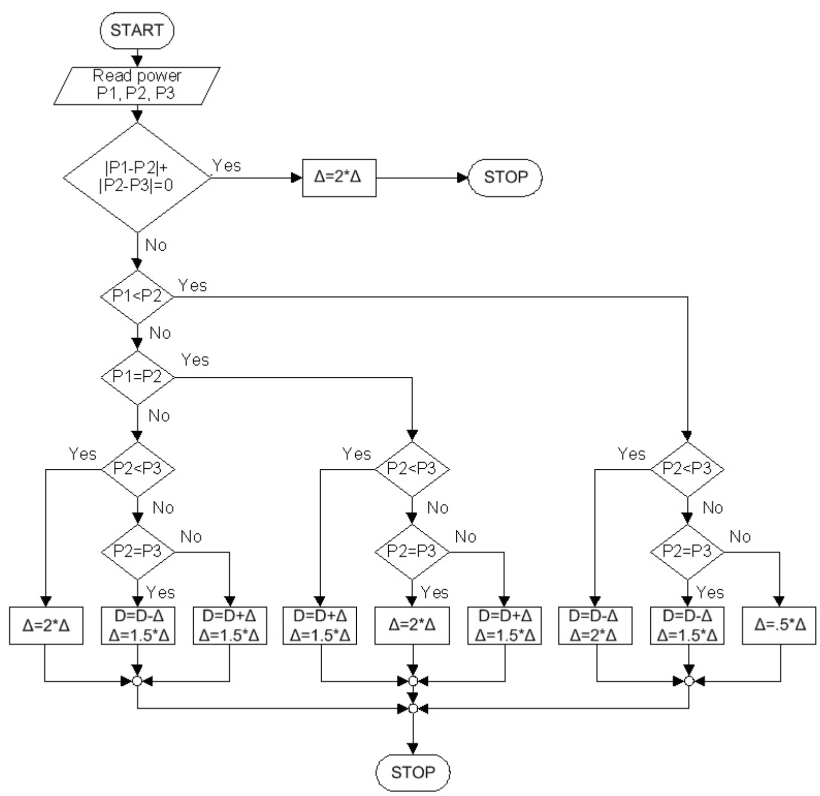

Fig. 8 The algorithm with three dynamic distanced points

5. Results

On the software simulation, we tested the algorithm presented in figure 8, on 8, 10 and 12 bits. The MPP tracking algorithm on 8 bits presented in [9] was used as reference. The bits number determines the discrete values that the duty cycle D can take. The newly developed algorithm uses a second variable Δ, for duty cycle adjustment, which values are dependent on the number of bits, too.

The two variables can take the following values:

$$\left\{ \frac{1}{2^B}, \frac{2}{2^B}, \frac{3}{2^B} \ldots \frac{2^{B-1}}{2^B}, 1 \right\} \tag{25}$$

where B is the number of bits used.

As any tracking algorithm has no problem in estimating the maximum power if the variations are very small or non-existent (corresponding to a sunny day without clouds), the images show the behavior of our algorithm in the case of a cloudy day, where relatively high variations in G and T.

Figure 9 shows the energy output of our cell array by using our tracking algorithm on 8, 10 and 12 bits compared to the literature 8 bits method [9]. The predicted duty cycle values will get the device very close to the computed theoretical maximal power point, obtaining tracking efficiencies near the maximum (100%).

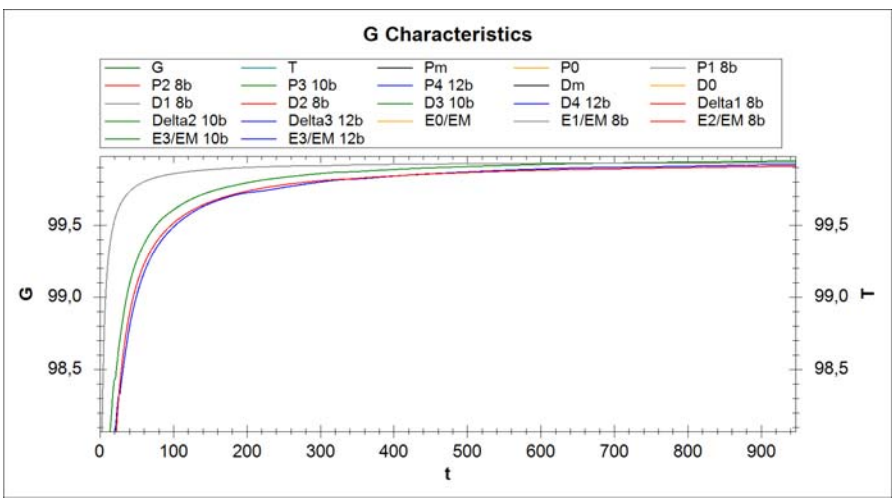

Fig. 9 The algorithm behavior: energy output

There is a small loss in energy in our algorithm for the first ~20ms until it tracks the correct values. This difference is only felt once at the algorithm's startup and is recuperated very rapidly (in ~2 seconds our algorithm becomes more efficient: 99,94% at 8 bits, 99,98% at 10 bits, while literature algorithm [9] is at 99,935%).

Figure 10(a) shows the power output of our cell array by using our tracking algorithm on 8, 10 and 12 bits compared to the [9] method on 8 bits and 10(b) shows a detail of the power tracking behavior.

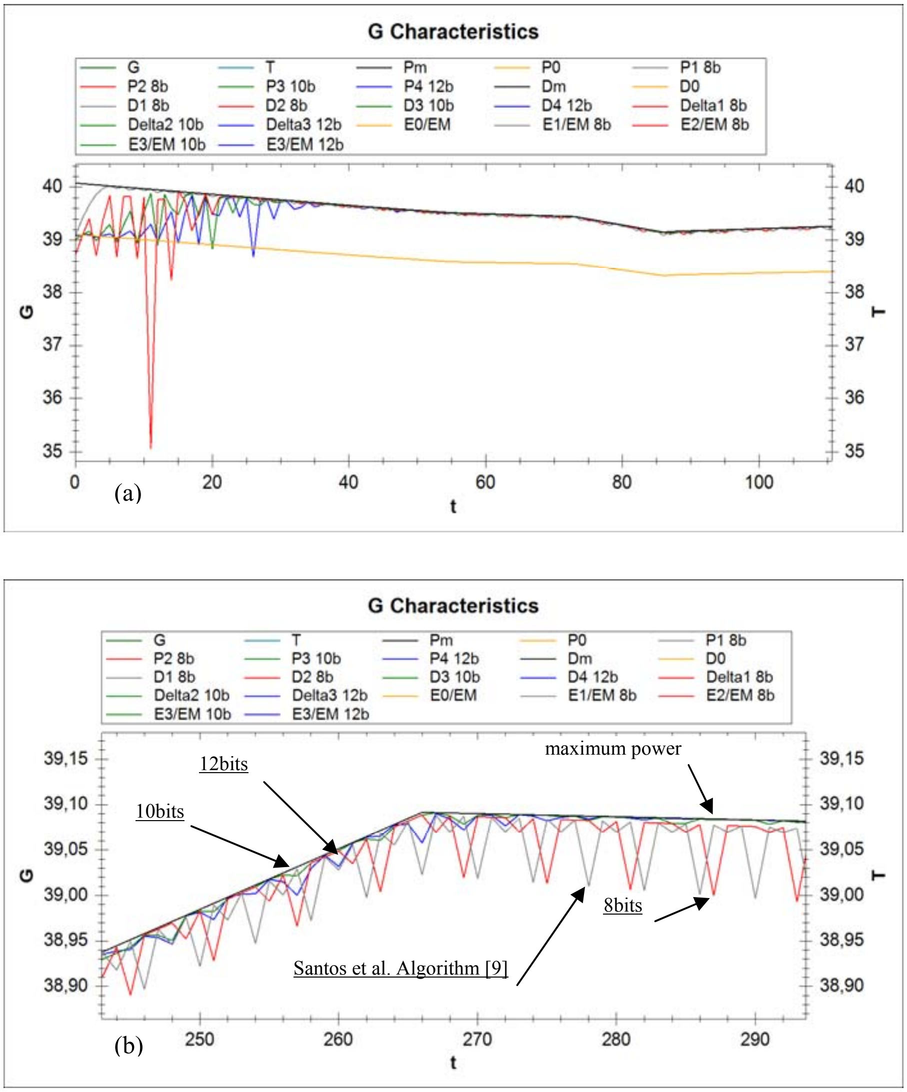

Fig. 10 The algorithm behavior: power output (a) and detail on power tracking (b)

The theoretical maximal power as seen in the figure is around 40 W. Our algorithm behaves best on 10 and 12 bits by staying as close as possible to the maximum power, while on 8 bits our algorithm's performance is still comparable to [9] algorithm.

Figure 11 shows that the algorithm needs about 50 ms (less than 15 steps) to calibrate the variables D and Δ.

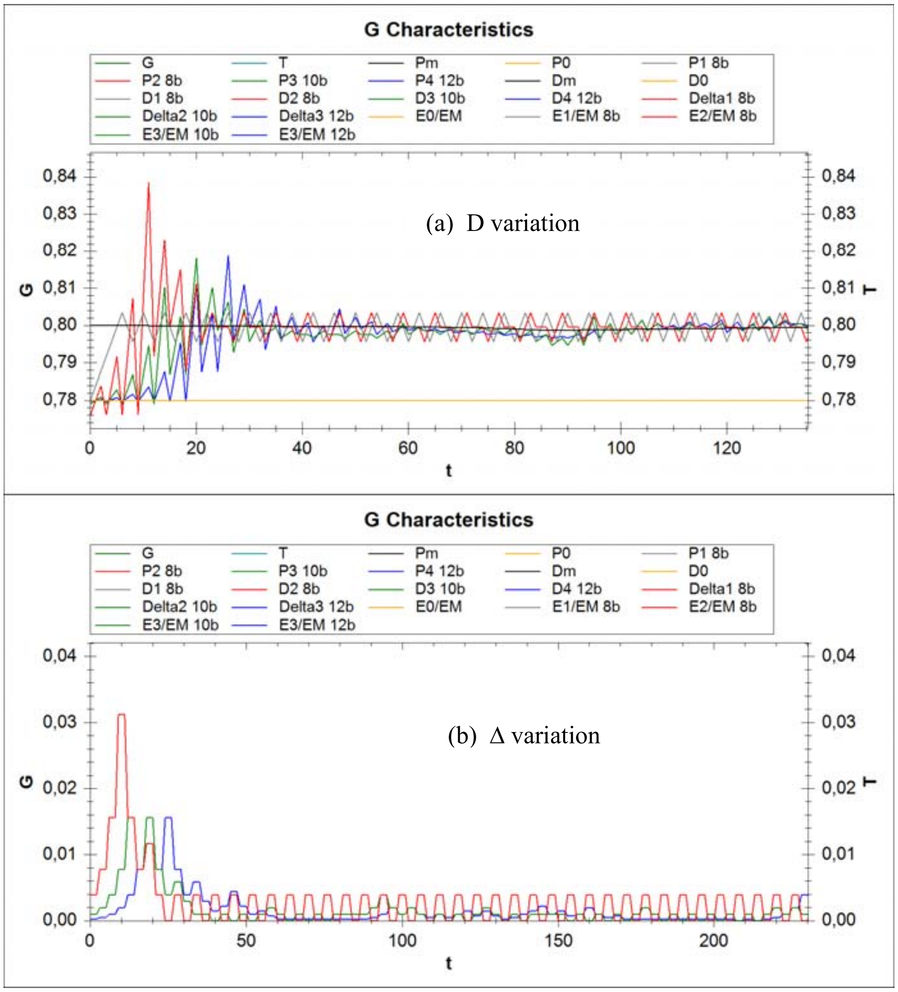

Fig. 11 The algorithm behavior: (a) D variation and (b) Delta variation

6. Conclusions

A general approach on modeling photovoltaic modules is presented. The proposed MPP tracking computational method is based on a boost converter control with an original algorithm. The algorithm is developed based on presented model and used a binomial search routine with three optimal determined power points. As shown in figure 12, the algorithm has a relatively short response time, covering the difference between extracting and available power, in less than 15 steps (~50ms). These results are very good compared with some widely-adopted MPPT algorithms [11]. The power loss depends on the working frequency of the control module. The algorithm starts from the known fact that the power curve at given conditions have a global maximum. This algorithm is useful for any kind of electrical energy source, where this condition is covered. The performance of the algorithm is limited by the precision of measurement blocks and by the word size of the microcontroller used. We intend to tune and develop the presented method to improve the response time and efficiency and to apply it to other kind of unconventional energy sources.

R E F E R E N C E S

[1] *H. Yang, W. Zhou, L. Lu, Z. Fang*, Optimal sizing method for stand-alone hybrid solar–wind system with LPSP technology by using genetic algorithm – Solar Energy 82 (2008), pp. 354–367

[2] *Bilodeau, K. Agbossou* - Control analysis of renewable energy system with hydrogen storage for residential applications – Journal of Power Sources 162 (2006), pp.757–764

[3] *Hossein Mousazadeh, Alireza Keyhani, Arzhang Javadi, Hossein Mobli, Caren Abrinia c, Ahmad Sharifi* - A review of principle and sun-tracking methods for maximizing solar systems output, ScienceDirect Online, 15 February 2009

[4] *R. Jallouli, L. Krichen, B. Francois and A. Ouali*, Modelling and Control of an Optimized PV Array with hydrogen System Comprising a PAMFC and an Electrolyzer – International Journal of Electrical and Power engineering 1 (3), (2007), pp. 264-273

[5] *Mellit, S.A. Kalogirou, L. Hontoria, S. Shaari,* Artificial intelligence techniques for sizing photovoltaic systems: A review – Renewable and Sustainable Energy Reviews 13 (2009), pp.406–419

[6] *Joanne Hui*, An Adaptive Control Algorithm for Maximum Power Point Tracking for Wind Energy Conversion Systems - A thesis submitted to the Department of Electrical and Computer Engineering in conformity with the requirements for the degree of Master of Science (Engineering) - Queen’s University Kingston, Ontario, Canada, December 2008

[7] *M.C. Kisacikoglu, M. Uzunoglu, M.S. Alam*, Load sharing using fuzzy logic control in a fuel cell/ultracapacitor hybrid vehicle, in International Journal of Hydrogen Energy 34 ,2009, pp. 1497 – 1507

[8] *O.C. Onar, M. Uzunoglu, M.S. Alam*, Modeling, control and simulation of an autonomous wind turbine/photovoltaic/fuel cell/ultra-capacitor hybrid power system, in Journal of Power Sources 185, 2008, pp.1273–1283

[9] *Jancarle L. Santos, Fernando Antunes , Anis Chehab, Cicero Cruz*, A maximum power point tracker for PV systems using a high performance boost converter – Solar Energy 80 (2006), pp. 772–778

[10] *R. Chenni, M. Makhlouf, T. Kerbache, A. Bouzid*, A detailed modeling method for photovoltaic cells – Energy 32 (2007), pp. 1724–1730

[11] *R. Faranda, S. Leva, V. Maugeri,* Comparative study of ten Maximum Power Point Tracking algorithms for Photovoltaic System - U. P. B. Scientific Bulletin, Series C, **Vol. 69**, No. 4, 2007, ISSN 1454-234x, pp. 271-278.