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A new approach in tracking maximum power under partially shaded conditions with consideration of converter losses

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Abstract

The fact that photovoltaic panels are very sensitive to non-uniform insolation conditions, which can occur several times a day, causes a decrease of efficiency and so increases time for return on investment. This work presents a maximum power point tracking algorithm (MPPT) operating on the load characteristic in order to take the converters losses into account. In addition, the proposed MPPT deals with the problems of shadowing for which the power-load characteristic can present two or more local maximums close to each other. Considering the converters losses it can be shown that the maximum output power of the photovoltaic panels does not necessarily coincide with the maximum output power of the converters. The proposed MPPT algorithm tracks the maximum power with the intention of reducing the total losses including those of converters. Its performance is verified by simulation and confirmed by experimental results.

Keywords: Photovoltaic array; Partial shading; Boost losses; Maximum power point tracking

1. Introduction

Growing interest in generating of green energy and environment protection has accelerated the development of photovoltaic technologies.

Partial shadowing or non-uniform insolation conditions is among the challenges to solve. Indeed, conventional maximum power point tracking algorithms (MPPT) show limitations to track the right maximum power point (MPP) in those conditions. Even if improved methods as proposed by Chao et al. (2009), Enrique et al. (2010), and Wang and Hu (2004) show great results for rapidly changing conditions, their algorithms may failed in case of multiple power maxima. In fact under non-uniform conditions, multiple local power maximums appear on the panel characteristic. Furthermore, this can happen several times a day, causing large deficit in terms of energy with a conventional MPPT.

Some works proposed solutions to solve this problem. Among these works, we mention the improved Fibonacci algorithm proposed by Ahmed and Miyatake (2008) which is a Perturb and Observe based MPPT (P&O) with variable step-size following the Fibonacci sequence. It uses an empirical function-condition that allows to know if the reached MPP is local or global. Another improved MPPT based on incremental conductance (IncCond) method with step-size variation was proposed by Ji et al. (2009). There, Partial Shadowing Conditions (PSC) is detected when two conditions on current and voltage are satisfied. Consequently,

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the proposed MPPT changes the voltage reference by linear function. In Ji et al. (2009), the power losses of proposed method is around 10% lower than conventional IncCond MPPT. Koboayashi et al. (2006) proposed a MPPT having two stages to deal with shadow. Their method requires an additional circuit for measurement, giving short-circuit current and open-circuit voltage. A new scanning, which reduces the time for tracking global peak power by skipping parts of the voltage range is proposed by Nge et al. (2009). Compared to the simple voltage sweep approach, the proposed method reduces energy loss during the scanning period by approximately 65% (Nge et al., 2009). Adaptive Perceptive Particle Swarm Optimization (APPSO) technique is proposed by Chowdhury et al. (2009) to control several photovoltaic (PV) arrays with one pair of voltage and current sensors. This method can reach MPP, under partial shading conditions, with an accuracy of almost 98% (Chowdhury et al., 2009).

In this paper, a new MPPT method for PV panel under PSC is proposed. The operating principle takes advantage of the conditions for recognition of global maximum presented by Ahmed and Miyatake (2008) and Ji et al. (2009). In addition, unlike other methods, the proposed MPPT operates on the converter output characteristic in order to include the effects of the converter losses and minimize their values. Under PSC for which the power-load characteristic can present two or more local maximums close to each other, we show that the maximum of the load power does not necessarily coincide with the maximum of the PV power. This can be explained by the fact that the values of the output current of PV panels at their peaks of output power are different, which leads to different power losses in the DC–DC converter, in cascade with PV panels. The proposed MPPT does not present any extra complexity compared to the classical ones. However, it increases significantly the efficiency of the PV installation under PSC. In addition, we will show that under uniform irradiance, the proposed MPPT leads to the same performances than classical approaches. Simulations and experimental results are presented on different configurations of the PV panels connections, to verify the performance of the proposed method.

2. PV cell, PV panel and PV array modeling

For modeling the PV cells, an enough precise equivalent circuit model (Fig. 1) is used since it is also quite simple to implement (Picault et al. (2010) and Jain et al. (2006)). In

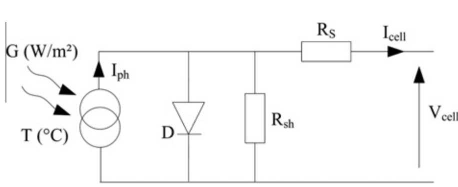

Fig. 1. One diode circuit model of a PV cell.

this model, the value of the current source (I_{ph}) is directly proportional to the light level on the cell and the diode (D) determines the I–V characteristic of the cell. Using Lambert-W function, the one-diode model is simplified (Jain et al., 2006 and Picault et al., 2010) and the Eq. (1) gives the explicit expression of the output current of each cell (I_{cell}) as a function of its output voltage (V_{cell}). Inversely, the voltage V_{cell} can be expressed as a function of the cell output current following Eq. (2).

$$I_{cell} = \frac{V_t}{R_S} \cdot \left[\frac{R_S \cdot (I_{ph}+I_o)}{V_t} - W\left(\frac{I_o}{V_t} \cdot R_S \cdot e^{\frac{V_{cell}}{V_t}} \cdot e^{\frac{R_S \cdot (I_{ph}+I_o)}{V_t}}\right)\right] - \frac{V_{cell}}{R_{sh}} \tag{1}$$

$$V_{cell} = V_t \cdot \left[\frac{R_{sh}}{V_t}.(I_{ph}+I_o-I_{cell}) - W\left(\frac{R_{sh}.I_o}{V_t} \cdot e^{\frac{R_{sh}}{V_t}.(I_{ph}+I_o-I_{cell})}\right)\right] - R_S.I_{cell} \tag{2}$$

where I_o is the diode saturation current [A]; I_{ph} the light-induced current [A] (depending on irradiance); V_t the thermal voltage; and R_S and R_{sh} series and shunt resistances. In this equation, W is the Lambert-W function defined by $W^{-1} : x \rightarrow x \cdot e^x$.

In our study we consider that each panel is the series associations of several PV cells (the *CHSM-175M* used in practice is an association of 72 cells in series). Each panel has two or more internal bypass diodes and a serial diode to avoid a reverse current in its PV cells. The output characteristic of each panel (panel output voltage of V_{PV} function of its output current I_{PV}) can be deduced from the cells characteristic (Eq. (2)) under any PSC by considering the activation conditions of different bypass diodes of the panel. By this way it is possible to obtain the characteristic $V_{PV}(I_{PV})$ and deduce $I_{PV}(V_{PV})$ for any PSC of the cells constituting the considered panel. A PV array is defined as the serial or/and parallel interconnection of several panels. Combining the out-put characteristics of different panels the array output characteristic can be deduced by considering the activation conditions of different protection diodes of different panels of the array.

Series connection of solar cells in an array is necessary to get needed voltage. A number of those strings are connected in parallel to get the required power. In order to estimate the impact of shadow on series and parallel cells arrangements, Ramaprabha and Mathur (2009a) have presented a comparative study of the power dissipated by cells for the two cases. The results prove that the shading is proportional to the dissipated power in the two configurations because produced power by highly illuminated cells is wasted as heat in the poorly illuminated cells (Ramaprabha and Mathur 2009b). Also they found that parallel connection dissipates less power than the serial connection. Nevertheless, the parallel configuration produces a high current, which imposes the effect of pulsed current on the panels and provokes the deterioration of energy quality.

Picault et al. (2010) also studied interconnections schemes and show the impact of mismatch losses due to shadowing phenomenon. To verify our purpose, the proposed MPPT algorithm is tested for different configurations of PV array interconnections.

In our study, for reducing the number of shadowed configurations, we supposed that the cells of each panel are operating under the same irradiance condition, even if different panels may be subjected to different light levels. Therefore, we use for a panel a similar model than used for each PV cell, we have then: $I_{PV} = I_{cell}$ and $V_{PV} = N_{series} \cdot V_{cell}$, where N_{series} is the number of serial cells of a panel.

3. Shadowing phenomenon

Non-uniform insolation conditions can reduce significantly the power delivered by the PV array. The impact of the shaded cells on the power produced can be very different depending on the interconnection scheme of different panels (Deline, 2009). Indeed, considering the above mentioned hypotheses over the panel modeling, the shaded panels are bypassed when they are in series connection with the other panels normally insolated and are open-circuited when they are in parallel. Then the produced energy depends on number of shadowed panels and their disposal.

As an example for simulation study, we consider one array of 6 panels organized in two serial groups of 3 parallel panels, as shown on Fig. 2. This configuration is named "*3p2s*" connection. When one of the serial groups having 3 parallel panels are shaded (Fig. 2), Fig. 3 show the output current–voltage characteristic of the array "*3p2s*" (I_{3p2s}–V_{3p2s}).This characteristic allows to obtain the output power–voltage characteristic (P_{PV}–V_{PV}) of this array (Fig. 4). Under the considered shadowing condition, two local maximums of almost the same power appear on the power–voltage characteristic corresponding to the distinguished values of array output voltage and current. As the losses in classical DC–DC boost converter depends to the output voltage or current of the PV array, we propose to use a MPPT algorithm maximizing the converter output power and including the converter losses. We need then to model the losses in different elements of the DC–DC converter and explain its control strategy.

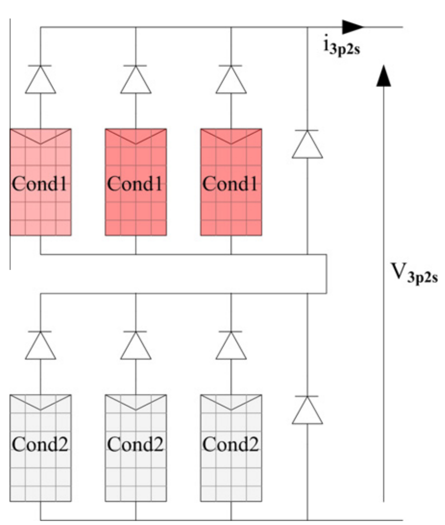

Fig. 2. Associations PV panels under different conditions (*cond1*: 1000 W/m^2 25 °C – *cond2*: 500 W/m^2 10 °C).

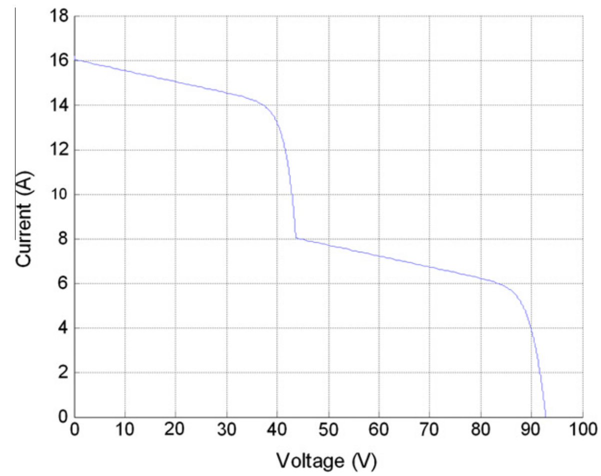

Fig. 3. Simulated output current–voltage characteristic of the "*3p2s*" array under PSC shown in Fig. 2.

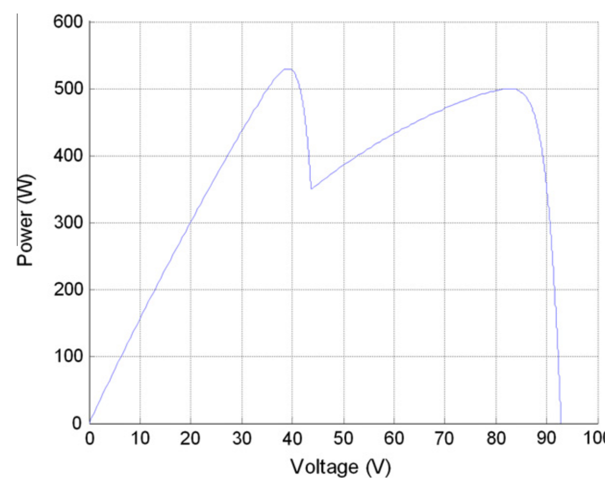

Fig. 4. Simulated output power–voltage characteristic of the "*3p2s*" array under PSC shown in Fig. 2.

4. Modeling and control strategy of the boost converter

The array output is connected to the load trough a boost converter. In the literature we found that most researchers use a voltage control (see for example Ji et al., 2009; Enrique et al., 2010), even if regarding the rapid dynamic response of photovoltaic PV array, the current control strategy seems more adapted for boost converter. Nevertheless, as the output V–I characteristic of the array under uniform irradiance (Fig. 5) is too sensitive to a small variation of the current around short circuit point, it is difficult to stabilize the control of the output current around high current values. As the proposed MPPT algorithm necessitates a scanning interval for detecting the global maximum power, a voltage control has been chosen.

Fig. 6 shows the boost converter including its parasitic elements like serial resistances and voltage drop across the switches. The boost converter can be modeled by Eqs. (3) and (4). As mentioned above, the control of array output voltage facilitates the boost control during scanning interval, to avoid the effect of pulsed current and allowing an easier control of the array output voltage a low value capacitor C_{pv} is connected to the array output (DC–DC converter input).

$$V_{PV} = L\frac{di_L}{dt} + r_L \cdot i_L + d \cdot (V_T + i_L \cdot r_T) + (1-d) \cdot (V_D + i_L \cdot r_D + V_S) \tag{3}$$

$$C_{PV}\frac{dV_{PV}}{dt} = i_{PV} - i_L \tag{4}$$

In our study we considered only a boost DC–DC converter. However, the proposed MPPT algorithm gives similar results with any kind of DC–DC converter long as converter losses are taken into consideration.

As mentioned above, the PV voltage is controlled to maximize either the PV array power (classical MPPT) or the DC–DC output power (proposed MPPT). In each case the used MPPT algorithm imposes the reference value of the PV voltage. Different approaches are used to control the PV voltage. For example Chu and Chen (2009) and Orozco et al. (2009) proposed a sliding control method. Here, we chose to control the voltage by controlling the charge of capacitor C_{PV}:

$$y = C_{PV} \cdot V_{PV} \tag{5}$$

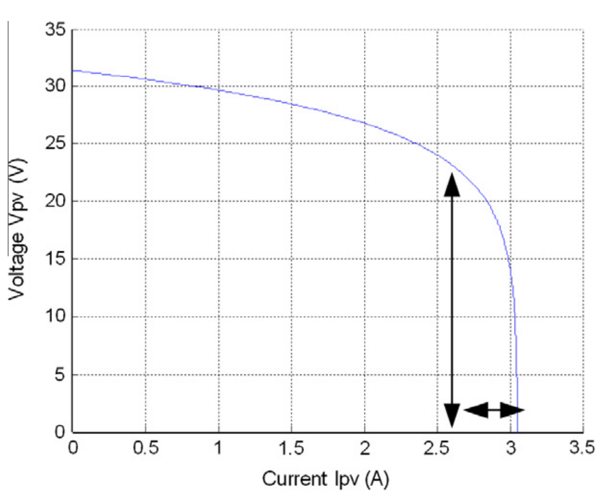

Fig. 5. Photovoltaic panel voltage versus current.

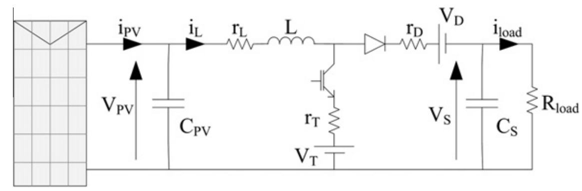

Fig. 6. Scheme of the boost converter with parasites.

To develop desired control, considering the boost converter modeled previously (Fig. 6), we consider the derivative given by Eq. (4):

$$\dot{y} = C_{PV} \cdot \frac{dV_{PV}}{dt} \tag{6}$$

Then we can deduce Eq. (5), where $\ddot{y}$ is our control variable:

$$\frac{di_L}{dt} = \frac{di_{PV}}{dt} - \ddot{y} \tag{7}$$

To ensure control, we use a third order control law as:

$$(\ddot{y}_{ref} - \ddot{y}) + K_1 \cdot (\dot{y}_{ref} - \dot{y}) + K_2 \cdot (y_{ref} - y) + K_3 \cdot \int (y_{ref} - y) = 0 \tag{8}$$

In view of Eqs. (2) and (3), we are able to determine the equivalent duty cycle d_{eq} allowing a good reference tracking:

$$d_{eq} = \frac{L \cdot (\frac{di_{PV}}{dt} - \ddot{y}) - V_{PV} + (r_L + r_D)i_L + V_D + V_S}{V_S + V_D + (r_D - r_T)i_L - V_T} \tag{9}$$

As $\frac{di_{PV}}{dt} = \frac{di_{PV}}{dV_{PV}} \cdot \frac{dV_{PV}}{dt} = \frac{di_{PV}}{dV_{PV}} \cdot \dot{y}$, we are able to express the transient current in the inductance as $\frac{di_L}{dt} = f(y, \dot{y}, \ddot{y}, \frac{di_{PV}}{dV_{PV}})$ ($\frac{di_{PV}}{dV_{PV}}$ is the derivative of the I_{PV}–V_{PV} characteristic and is limited). By choosing appropriate regulation parameters, the transient current ($\frac{di_L}{dt}$) can be limited.

Parameters K_1, K_2 and K_3 can be chosen following Eq. (8):

$$\begin{cases} K_1 = 2 \cdot \zeta \cdot \omega_n + p_1 \\ K_2 = 2 \cdot \zeta \cdot \omega_n \cdot p_1 + \omega_n^2 \\ K_3 = \omega_n^2 \cdot p_1 \end{cases} \tag{10}$$

where p_1, ω_n and ξ are the regulation parameters.

For the case that the switching frequency is fixed to $f_s = 20$ kHz, we chose $\omega_n = 1000$ rad s^{-1}, $\zeta = 0.7$ and $p_1 = 100$ rad s^{-1}.

To verify the performance of the proposed voltage control, simulation has been done in the case that a PV panel is connected to a resistive load through the boost converter. Fig. 7 shows the results simulations concerning a voltage step response when irradiance condition change from 1000 W/m^2 to 500 W/m^2 for one PV panel. In this simulation, voltage reference is a step from 38 V to 40 V. These results validate the proposed control. Indeed as we can see on Fig. 7, PV voltage V_{PV} follows its reference in less

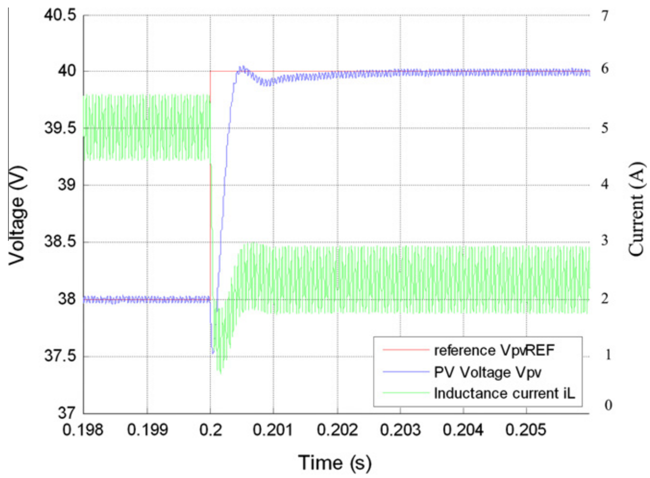

Fig. 7. Voltage control performance verification.

than 10 ms. We can also verify that the inductance transient current is limited and there is no risk for semiconductor components. Such rapidity of voltage response is far enough for our application, shadowing phenomenon and condition variations being slower.

5. Proposed MPPT algorithm

The proposed MPPT is able to track the global maximum of $P_{Load} = Vs \cdot i_{Load}$. A binary condition called "restart" allows detecting a wrong maximum operating point ("restart" passes from "1" to "0"), then after a new scanning; a conventional P&O technique with step-size variation allows determining the new reference value of the array output voltage (V_{array}), which is imposed by the proposed control strategy. The flowchart of the algorithm is shown on Fig. 8. By this algorithm an incorrect maximum operating point can be detected using two distinct conditions. The first one, *cond1*, as explained by Ahmed and Miyatake (2008), corresponds to the satisfaction of the following equation:

$$\frac{|P'^{(i)}_{(V_{2-d})} - P^{(i-1)}_{(V_{1+d})}|}{P'^{(i)}_{(V_{2-d})}} > r \qquad (11)$$

where $P^{(i-1)}_{(V_{1+d})}$ is the measured power at step $(i-1)$. The binary number d becomes "1" if the value of V_{array} at step (i) is greater than its value at step $(i-1)$ and "0" inversely. $P'^{(i)}_{(V_{2-d})} = \frac{P^{(i)}_{(V_{2-d})} + P^{(i-1)}_{(V_{1+d})}}{2}$ is an estimation of the power at step (i) assuming linear variations. Parameter r in Eq. (9) takes the value around 0.2 and is adjusted experimentally.

Secondly the *cond2* corresponds to partially shaded conditions when Eqs. (12) and (13) are both satisfied, Ji et al. (2009) show:

$$\Delta V_{pv} = V_{pv}[i] - V_{pv}[i-1] < \Delta V_{set} \qquad (12)$$

$$\frac{\Delta I_{pv}}{I_{pv}[i-1]} = \frac{I_{pv}[i] - I_{pv}[i-1]}{I_{pv}[i-1]} < -\Delta I_{set} = \frac{-I_{pv}[i]}{N_{pp}} \qquad (13)$$

where N_{pp} is the number of parallel panels; ΔV_{set} is determined experimentally.

The conditions *cond1* and *cond2* have been empirically determined and may fail (Ahmed and Miyatake, 2008 and Ji et al., 2009). In addition, in most of the cases, *cond1* and *cond2* give the same results. Therefore, we decided to combine them. Finally the condition ordering our algorithm to restart a scanning when one or other condition is satisfied: restart = *cond1* + *cond2*.

The scanning part of our algorithm starts imposing $V_{ref} = V^{min} = 10$ V for 0.1 s so that the scanning begins with a stabilized array output voltage. Here, we suppose that the global maximum of the characteristic is located for reference voltage higher than V^{min} (always true in practice). Then a ramp voltage reference with a slope of α is imposed to obtain the entire characteristic until V^{max}. The ramp α is chosen so that the scanning is fast enough to avoid significant variations of external conditions.

Unlike other MPPT methods (Ahmed and Miyatake, 2008; Ji et al., 2009; Koboayashi et al., 2006; Nge et al., 2009), the proposed algorithm aims to maximize the DC–DC converter output power. As the experimental results have shown, especially under certain PSC, the converter losses are considerably reduced.

After the scanning process, a P&O algorithm with variable step starts (Ahmed and Miyatake, 2008). Here we used a new approach to determine the step-size variation following the sequence $n \to n^2$. Parameter n is chosen to be between 1 and 7 (corresponding to a variation in step size from 1 to 49). Voltage reference variation is adjusted with parameter K with a value fixed regarding the stability wanted when MPP is reached.

6. Simulation results

This section presents the simulation results of the proposed MPPT algorithm. The simulated PV array is the same as in part 3 ("*3p2s*" connection under specific PSC shown in Fig. 2). In this case, there are two very close power peaks of PV array, but the corresponding currents are relatively different (see characteristic on Figs. 3 and 4).

Fig. 9 shows that the proposed algorithm is working as predicted (global maximum reached). It also shows the importance of taking into account the DC–DC converter losses under non-uniform insolations. Indeed, the global maximum power peak of the power generated by PV array is different from the global one seen by load. As expected, our algorithm maximizes received power; even if the array produces around 6% less than it maximum possible when MPP is reached (500 W instead of 530 W possible), the load receives around 10 W more (475 W instead of 465 W), i.e. in this case the global efficiency increased by around 2% using the proposed MPPT including the converter losses. Furthermore, as the array and inductance currents are lower in this point (Fig. 4), losses in the converter are also reduced. In fact, using the classical MPPT the converter losses are equal to 65 W (530–465 = 65 W).

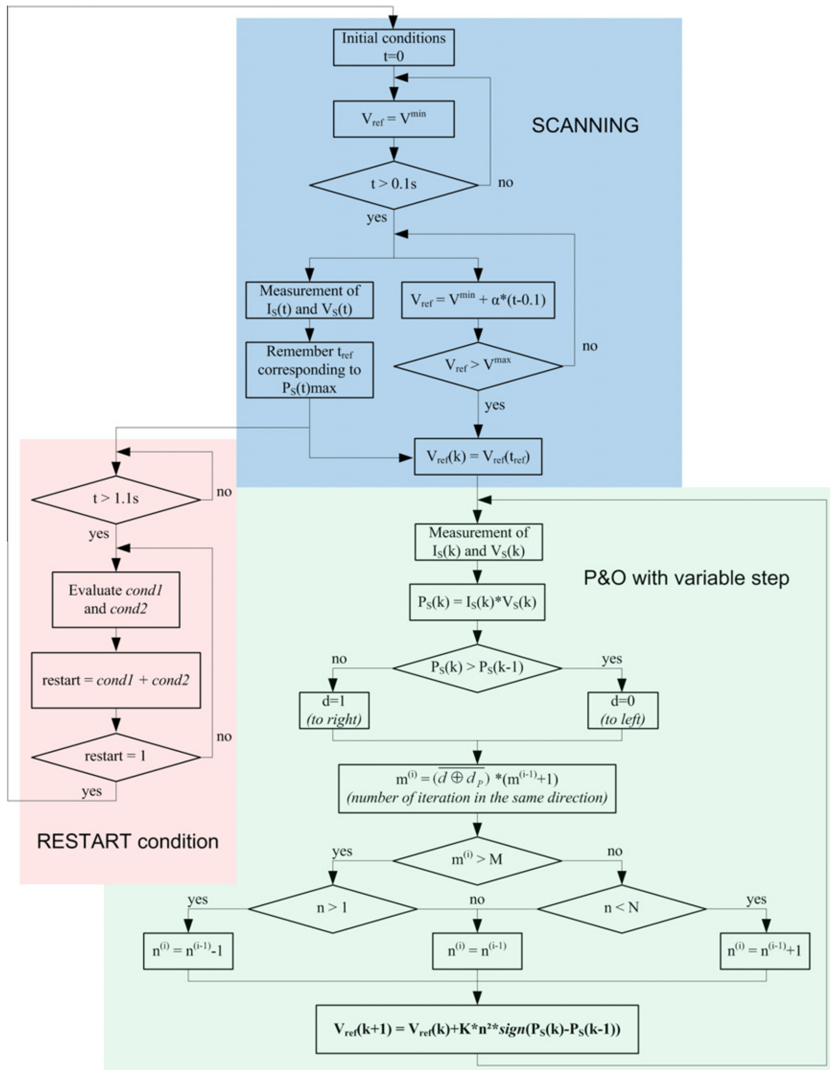

Fig. 8. Flowchart of the proposed MPPT algorithm.

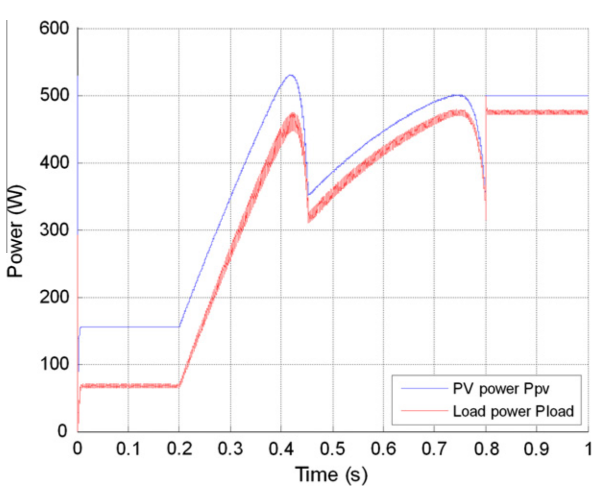

Fig. 9. Simulation results with the proposed MPPT algorithm.

Using the proposed MPPT these losses reduce almost 62% >(500–475 = 25 W) under the mentioned shadowing condition. As the converters life duration is related to the number of imposed thermal cycling, the proposed MPPT may lead to an increase in their life time, especially when the similar shadowing conditions are frequent.

7. Experimental results

To confirm simulations results, the MPPT algorithm is tested experimentally. The tested system consists of 6 PV arrays from series *CHSM-175M*. Under standard conditions, i.e. insolation of 1000 W/m^2 and temperature of 25 °C, the open-circuit voltage of each panel is 44.30 V, with a short-circuit current of 5.35 A. In those conditions, the datasheet gives for such a panel a maximum power of 175 W for a voltage of 36.3 V and a current of 4.8 A.

The boost converter used for these manipulations is connected to a resistive load and made with the following parameters (Fig. 6): $L = 1$ mH; $r_s = 0.1\ \Omega$; $C_{pv} = 120\ \mu$F. The load could be an active load, but it would not change the principle of validation of the advantages of the proposed MPPT algorithm compared to the classical ones.

To ensure a good maximum power point tracking in any configurations, we present results for three different connections of the 6 panels: all connected in series (array *6s*), all in parallel (array *6p*), and a combination of both, 2 assembly of 3 parallel panels in series (array *3p2s*). For each of the following results, the PV array voltage is imposed to be 10 V before scanning starts, which is less than the optimal value as mentioned in Section 5. Shadowing condition is realized in practice by covering part of the PV array with sheets of paper.

As during each scanning interval, the array voltage reference varies linearly (with a fixed ramp), the time variation of array output power is similar to the output power–voltage characteristic of the array.

We consider first a PV array composed of 6 panels connected in parallel (array *6p*). Under standard conditions, the open-circuit voltage of this PV array is 44.30 V and its short-circuit current 32.1 A. Fig. 10 shows the results concerning the array *6p* under PSC. First, we observe that the proposed MPPT algorithm is working as predicted. After a short period (less than 1 s) for scanning the output power–voltage characteristics of the array and the boost converter, the load power is stabilized around its maximum value (180 W) with small variations (P&O part of the algorithm). Secondly, we can verify the benefit of maximizing the converter output power instead of the PV array one. Fig. 11 shows results under the same conditions (insolation, temperature, shadow), with a classical MPPT algorithm maximizing PV array output power. We notice that the optimal values of the array output voltage using the proposed and classical MPPT algorithms are different (corresponding to two different global maximum on the characteristics). This second maximization leads to a lack of power received by the load of around 10 W. Under these shadowing conditions, the proposed MPPT method, including the converter losses, leads to a higher efficiency (5% more). Furthermore, as mentioned in Section 5, the main advantage of the proposed method is the considerable reduction of inverter losses under certain PSC. Indeed, when MPP is reached, the converter losses are almost 25 W with the proposed MPPT (Fig. 10) and 35 W with the classical MPPT (Fig. 11), i.e. 30% less losses with the proposed MPPT.

The second series of experimentation concerns the PV array of 6 panels interconnected as shown in Fig. 2 (configuration *3p2s*). Under standard conditions, the array has an open-circuit voltage of 88.6 V and a short-circuit current of 16.05 A. Under a given PSC, Fig. 12 shows all advantages of the proposed method. Indeed, we can see that the

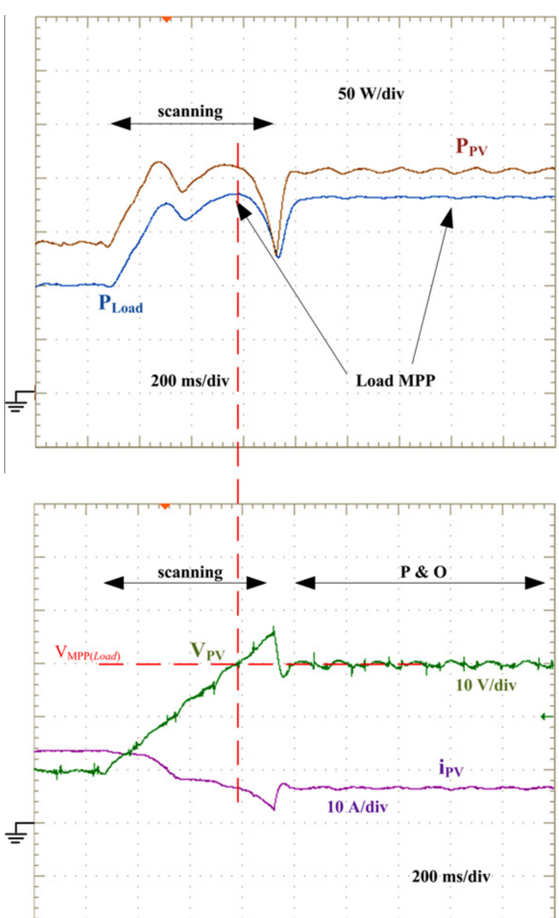

Fig. 10. Results with proposed MPPT (array *6p*).

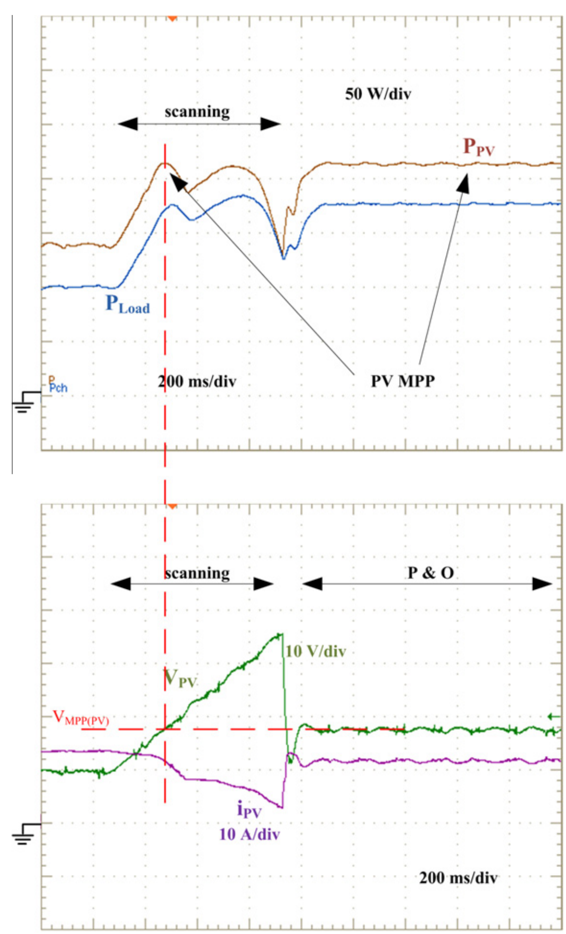

Fig. 11. Results under same climatic conditions (array *6p*) – MPPT on PV power.

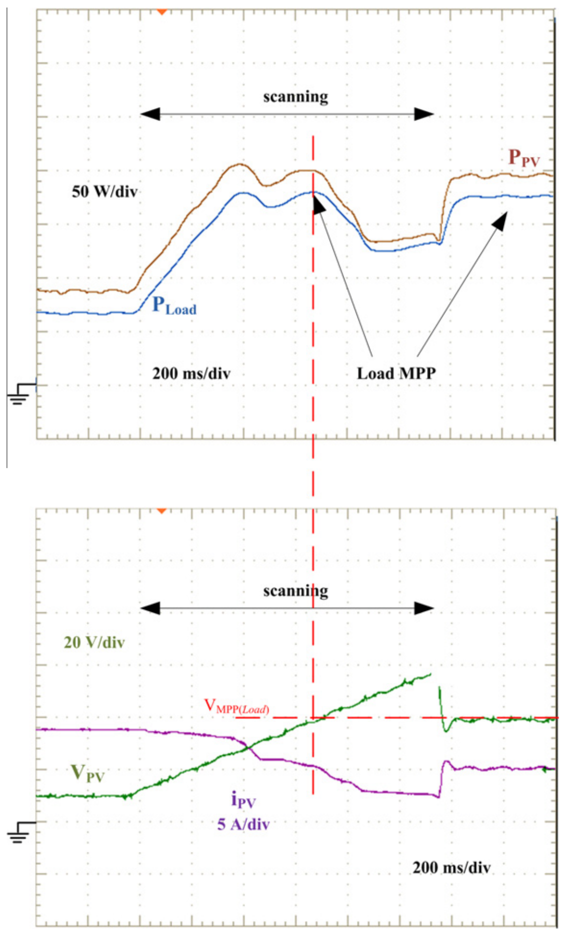

Fig. 12. Proposed MPPT results (array *3p2s*).

maximum values of the array output power ($P_{array,\ max}$) and converter ($P_{Load,\ max}$) correspondent to two different values of array output voltage. The proposed MPPT maximizes the load power and improves the PV system efficiency by around 2%. The efficiency improvement is less than the previous results (Fig. 10) due to the fact that the tests are carried on under different PSC and for two different configurations. However, we note that the converter losses are again reduced using the proposed MPPT (20 W instead of 30 W with classical MPPT).

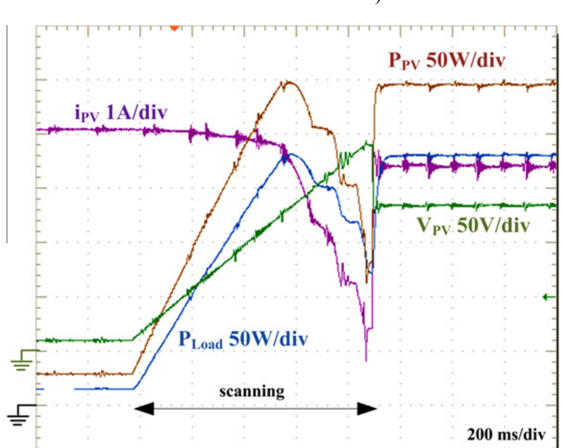

Fig. 13. Results with proposed MPPT (array *6s*).

The last experimental results concern a PV array with 6 panels in series (array *6s*). Even if the output power–voltage characteristics of the PV array and the converter both have three local maximums, their global maximums correspond to the same array output voltage due to the particular PSC (Fig. 13). In this case, the proposed MPPT leads to the same performances that can be achieved with a classical MPPT. However the scanning procedure allows avoiding the PV system operating around a local maximum power.

8. Conclusion

In this paper, a novel approach for tracking a global maximum under partial shading conditions is proposed. This method operates on the DC/DC converter output power characteristic and includes converter losses influence.

In view of the literature and by using Lambert W-function-based model for a PV cell, we obtain a PV array model taking account of partial shadowing conditions. By including the converter losses for power maximization, we show that output PV array maximum power does not necessarily coincide with the converter output maximum power. Then under certain PSC, maximizing the converter output power improves the total efficiency. Furthermore, at the same time, the proposed method leads to significantly reduce losses through the converter. This results in a longer lifetime for the converter due to a lower self-heating cycling under these PSC.

To verify the performance of the proposed MPPT method, simulations and experiments are performed. From shown results, it is confirmed that operating on the converter output power characteristic allows better performances under PSC by increasing the efficiency and reducing losses through the converter.

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