Dynamic Maximum Power Point Tracking Method including Detection of Varying Partial Shading Conditions for Photovoltaic Systems

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Keywords

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Abstract

Photovoltaic (PV) systems, being one of the promising power generation systems, need performance optimization typically under partial shading conditions (PSCs). In such non-uniform irradiation conditions, not only conventional maximum power point tracking (MPPT) algorithms but also advanced techniques fail in operating at the power peak. So, global maximum power point tracking (GMPPT) methods are needed when several local maximum power points exist under PSCs. The major difficulty is not in detecting the GMPP but in finding the new one when the PSCs change. Consequently, the challenge becomes in detecting the variation of PSCs. The proposed method relies on monitoring the rate change on power at the output of the PV panel. Proving that this criterion alone is not accurate, a measurement Q is introduced and used as a watchdog for critical partially shaded cases. When in such case, a timer alternates between a scanning process and a dual-mode MPPT method based on perturb and observe (P&O) and constant voltage algorithms. Otherwise, the MPPT work in not interrupted unless a drastic power change takes place. The proposed algorithm proved its efficiency in all partially shaded irradiation conditions when implemented in a MATLAB/Simulink environment. Furthermore, it is compared to other partial shading detection (PSD) methods to verify the algorithm's performance in a generic case.

Introduction

Due to the increase of global environmental concerns, countries' intention and investment in finding solutions have grown over the past decade. As a result, the past 20 years have witnessed high deployment and integration of solar photovoltaic (PV) systems. Although PV energy remains one of the most promising eco-friendly sources of energy, several proceedings need to be treated in order to raise its efficiency. The performance of PV systems is greatly influenced by climatic conditions like sunlight, ambient temperature, airflow, dust, clouding, etc. Solar irradiation and temperature intervene explicitly in the model of the PV panel. Clouding or any shadow, creates non-uniform irradiation on the surface of the PV panel. Consequently, partial shading conditions (PSC) occur and produce a different form for the characteristic PV output [1].

To ensure operating at the maximum power point (MPP), many maximum power point tracking (MPPT) techniques were developed: conventional MPPT (P&O based [2, 3], Inc-Cond based [4, 5]) and advanced intelligent methods (fuzzy logic [6], neural networks [7]). Although these techniques show great performances under uniform irradiation, they fail to track the global maximum power point (GMPP) when PSCs occur [8]. In order to detect the global maximum, several algorithms suggest novel GMPPT methods. Most GMPPT algorithms propose a search method for the GMPP [9, 10].

Since some energy is lost during the search interval, the interest in reducing the duration or the occurrence of these searching mechanisms has increased. Therefore, the need for PSC detection methods has become important to avoid unnecessary searches. Partial shading detection (PSD) techniques proposed in literature used different criterion mainly relying on the variation of electrical measurements like power, voltage and current. For example a monitoring of current and voltage variation along with a fast tracking technique is proposed in [11]. Some PSD methods are based on the number of sign changes of voltage and power respectively [12, 13]. Also, adding to the power variation verification two equations based on voltages changes are suggested for instance in [14]. Other techniques propose examining the climatic conditions while monitoring only open-circuit and short-circuit measurements, such as [17, 18].

However, in some scenarios, most methods fail to detect any change in climatic conditions. These scenarios are presented later and critical PSC are discussed. Some methods eliminating these critical cases rely on hardware solutions [15] or computational solutions [16]. The proposed semi-dynamic GMPPT technique guarantees maximum power transfer in all varying climatic conditions and takes into consideration the critical cases without additional sensors or calculators. When an irradiation change occurs, a quick scan is launched to detect the new maximum power point whether there are many MPP or just one. When the GMPP is found, dual-mode algorithm, an adaptive P&O based technique, operates to stabilize the system with minimum steady-state oscillations. Expressly, the scanning mechanism starts if there is a sizable variation in power P_{PV} or if a possible critical case is detected. The transitions between subprograms are smoothed by varying the duty cycle which controls the DC/DC converter. The proposed aperiodic scan GMPPT method is tested in a MATLAB/Simulink environment under varying partial shading conditions and compared to a classical technique that does not consider critical cases.

System description

To form a PV plant, several modules are generally connected in series in order to attain a certain voltage, forming strings. The latter are connected in parallel to allow reaching a required current. The impact of shadow differs according to the electrical interconnection and the PV panel orientation. Several researches analyse the role of PV array size and configuration [19, 20]. Series-Parallel (SP) remain widely implemented due to its simplicity along with the Total Cross Tied (TCT) scheme that proved to offer the least mismatch losses.

During this work, the PV array studied regroups three PV modules in series creating a single PV string. The mismatches caused by PSCs can be generalized later when several strings are connected in parallel (SP configuration). A Conergy PowerPlus 214P PV module is chosen and used in simulations and for measurements. This choice is conditioned by the presence of these modules in the laboratory installation. A stand-alone PV system is considered in order to test the proposed control method (Fig. 1), so the PV array is only supplying a resistive load R. The impedance matching is adapted by a DC/DC quadratic boost converter whose role also includes voltage output regulation and maximum power extraction. The proposed converter structure presents two major advantages: a high voltage conversion ratio and having one controllable switch. The components used in the quadratic boost converter are presented in Table I. The control strategy calculates the value of the duty cycle commanding the MOSFET switch via a PWM block with a switching frequency of $10kHz$. The global maximum power point tracking algorithm provides the optimal value for the duty cycle in real-time. The strategy uses only the voltage and the current measured at the output of the PV array, hence minimizing the number of sensors in such configurations.

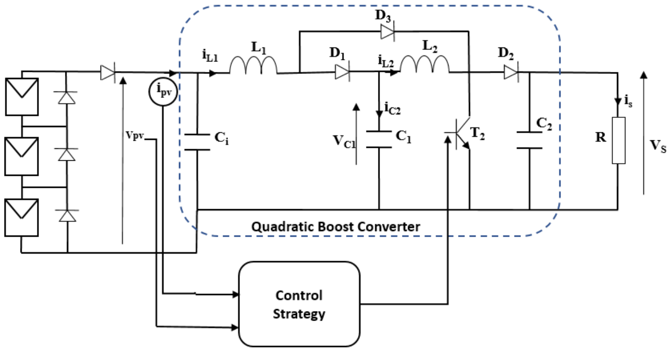

Fig. 1: Stand-alone PV system synoptic

Table I: Quadratic boost converter's parameters

C_i	L_1	r_{L1}	L_2	r_{L2}	C_1	C_2	R
$4.7\mu F$	$5mH$	$52m\Omega$	$10mH$	$134m\Omega$	$470\mu F$	$220\mu F$	150Ω

Proposed control strategy

Critical partial shading conditions

Various GMPPT methods suggest a curve tracing to locate the GMPP whether its a full scanning or a two points verification. During the search process, the GMPPT work is interrupted and the available energy is not all harvested. Consequently, it is more beneficial to avoid needless search when the PSC does not change. In order to detect the change in the climatic conditions, partial shading detection (PSD) methods are developed [11, 12, 13]. Several techniques monitor the variation of successive measurements of PV panel output variables: P_{PV}, I_{PV} and/or V_{PV}. Although many techniques proved good performance in varying PSC, they still fail to detect the change of irradiation in some cases. These cases are critical because P_{PV}, I_{PV} and V_{PV} do not vary. This happening occurs when the GMPP in the old irradiation profile is also a LMPP in the new irradiation pattern. Several irradiation profiles are investigated on a PV string formed by three PV modules in series, and each module is shunted by a by-bass diode. Some of the tested patterns are presented in Table II along with their P-V and I-V curves (Fig. 2 and Fig. 3 respectively).

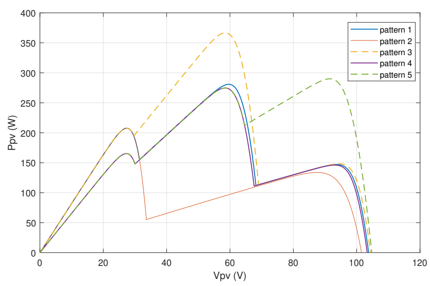

Fig. 2: P-V curve under different irradiation patterns

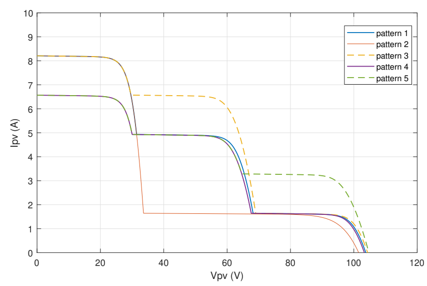

Fig. 3: I-V curve under different irradiation patterns

When the GMPP position is at the most left, the MPP current reaches its maximal possible value (as seen graphically for pattern 2). Expressly, the current delivered from the PV string is imposed by the PV module most exposed to sunlight since other modules are shunted. Therefore, even if one of the less illuminated modules encounters an increase of irradiation (for example a transition from pattern 2 to pattern 3 occurs), the corresponding diode remains conductive. The global current is intact and the change of irradiation is not perceived. Consequently, the PSD algorithm does not detect the need to scan

Table II: Irradiation values on the PV array in W/m^2

Pattern 1	Pattern 2	Pattern 3	Pattern 4	Pattern 5
1000	1000	1000	800	800
600	200	200	600	600
200	200	800	200	400

and notable power is lost because the operating MPP (still the most left) is not the GMPP of pattern 3. By analogy, this happening can occur in an all-parallel configuration so one module imposes its voltage and the increase of irradiation of the shaded module is imperceptible. In order to overcome these critical cases, the proposed method suggests a periodic scan when the GMPP is to the most left. One of the main advantages of this technique is being also suitable for systems with another configuration and having a larger number of modules. The challenge remains in finding whether or not the GMPP is the local maximum point most to the left.

Aperiodic scan-dual-mode

The proposed aperiodic scan technique combines two programs: a P-V curve scanning method and a MPPT algorithm for rapidly changing irradiation. The transition from one sub-program to another is subjected to different conditions. The flowchart of the proposed technique is shown in Fig. 4 where the scanning process, the MPPT dual-mode algorithm and the transition criteria are presented.

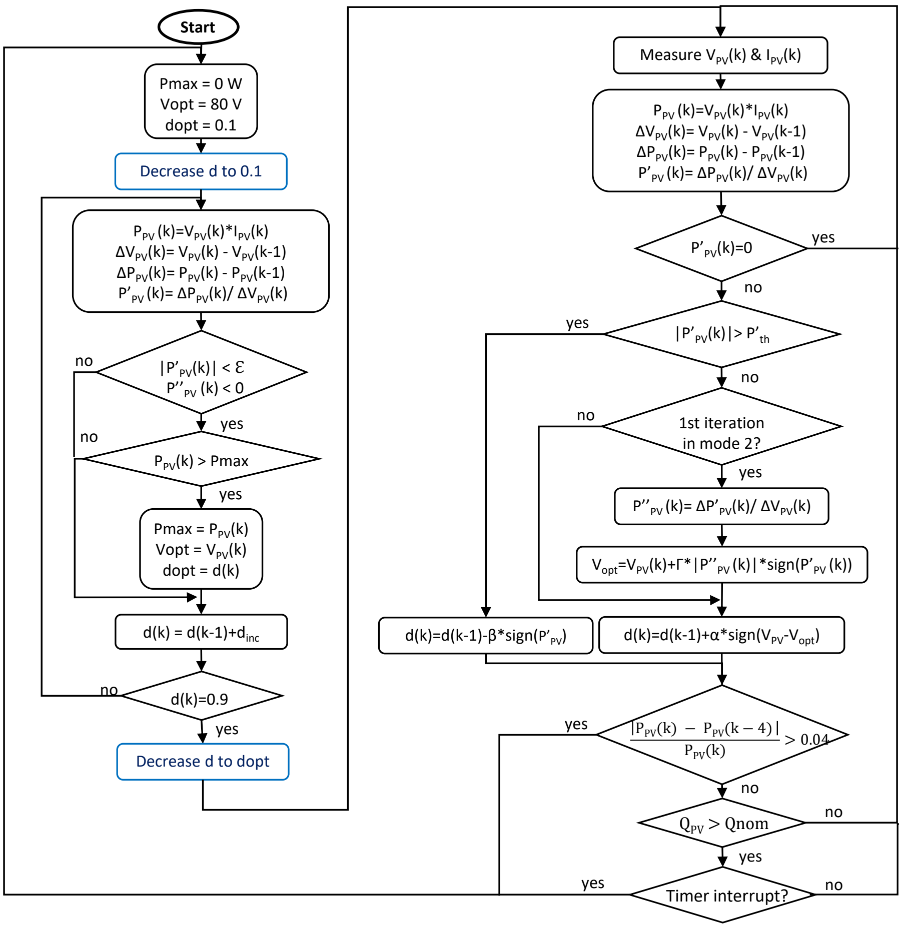

Fig. 4: The flowchart of the global algorithm

Dual-mode MPPT algorithm is a hybrid between the algorithms constant voltage and fixed step P&O. So, in mode 1, the operating point is far from the MPP, the P&O with a large step is activated for rapid convergence. The step's expression is based on the gradient method:

$$\delta d = -\beta * sign(P'_{PV}) \tag{1}$$

Where β is a constant whose value impacts the response time. However, in mode 2, the goal is to approach the MPP as close as possible so the algorithm brings the output voltage V_{PV} near its optimal value at MPP. Therefore, the oscillations in steady-state are significantly reduced. In this mode, the duty cycle step is constant:

$$\delta d = \alpha * sign(V_{PV} - V_{opt}) \tag{2}$$

Where α has a relatively small value. The optimal value of V_{PV} is estimated using the expression (3) found by comparing the curves P'_{PV} and P''_{PV} in terms of V_{PV} at different irradiation around the MPP.

$$V_{opt} = V_{PV} + \Gamma * |P''_{PV}| * sign(P'_{PV}) \tag{3}$$

Where Γ is a fixed constant. The value of V_{opt} can be verified later with the voltage value measured at the GMPP during the scan. The shifting from one mode to another is made by comparing the value of P'_{PV} to a threshold P'_{th}. The value of the power derivative with respect to the voltage is high in transient response while it approaches zero around the MPP. Expressly, when P'_{PV} is higher then P'_{th}, mode 1 is operating; otherwise, mode 2 is launched. The values of Γ and P'_{th} are chosen manually to approach the MPP. The chosen values for all the algorithm constants are: $\alpha = 0.001$, $\beta = 0.005$, $\Gamma = 0.5$ and $P'_{th} = 5$.

The proposed aperiodic scan-dual-mode method monitors continuously the variation of successive measures of P_{PV}. When the absolute difference between two consecutive PV output power values exceeds a threshold value, a scanning process is launched. The threshold value is a ratio of the current P_{PV} measure, it is determined to be superior to the steady-state power oscillations. Since the proposed dual-mode MPPT method presents the advantage of very small oscillation, the power threshold is fixed to 4%. The expression of the first scan-triggering criterion is:

$$\frac{|P_{PV}(k) - P_{PV}(k-4)|}{P_{PV}(k)} > 0.04 \tag{4}$$

However, in light of the above analysis, even if this criterion (4) is not met, partial shading variation might have occurred. This occurrence could be the result of critical partial shading conditions variation. Consequently, a critical case verification test is carried out, presenting the second scan-triggering criterion. A new indicator is introduced: the conductance $Q_{PV} = \frac{I_{PV}}{V_{PV}}$. The LMPP most to the left is characterized by a Q_{PV} relatively high because around left LMPP the current is maximal and the voltage is minimal. Therefore, the conductance of the current MPP is calculated. If Q_{MPP} exceeds the nominal value $Q_{nom} = \frac{I_{MPP,nom}}{V_{MPP,nom}}$, the current MPP is then positioned to the left. Hence, while the PV power has not changed, a scan is launched every T seconds. The periodic scan eliminates the critical cases without any considerable loss. In order to smooth the transitions from the dual-mode MPPT to the scanning process, the duty cycle is decreased from its current value to 0.1. After the scan, where the P-V curve is traced by varying the duty cycle from 0.1 to 0.8, the transition back to MPPT happen by decreasing the duty cycle down to its value at the GMPP. The smoothing blocks are presented in blue on the flowchart Fig. 4.

Validation and results

The proposed PV system (shown in Fig. 1) is evaluated in a Simulink/MATLAB environment for different shading patterns. In this paper, the PSCs scenario presented shows the occurrence of a critical case to verify the performance of the proposed approach. Then, the suggested method is compared to a similar approach only without the criterion Q which is the major inclusion in this algorithm. First, the scenario considered starts with the non-uniform irradiation conditions of pattern 1. Then at $t = 4s$, the change of PSCs occurs so the PV array becomes subjected to pattern 2. Finally at $t = 8s$, the shading pattern is set as pattern 3. All pattern curves and values are presented in Fig. 2, Fig. 3 and Table II respectively.

The performance of the PV system under the proposed scenario is shown in Fig. 5. From start to $t = 4s$, the PV array is subjected to pattern 1. The system is launched with a scan then dual-mode MPPT starts operating after finding the GMPP and its parameters. So, the algorithm operates at the GMPP with $P_{PV} = P_{GMPP} = 277W$. The proposed method guarantees minimum oscillations around the GMPP due to the choice of small step and the measurement accuracy of V_{PV}. Since there is no climatic change, the conductance is tested: $Q_{PV} = 0.076A/V$ is less than $Q_{nom} = 0.087A/V$, hence no periodic scan is needed.

At $t = 4s$, a change in irradiation to pattern 2 occurs which causes a high drop in power satisfying criterion (4). So, the scanning process is launched, and the new GMPP is found. Again, the proposed alternation between the scan and the dual-mode algorithm allows reaching the global maximum point quickly and staying around it with reduced fluctuations ($P_{PV} = 202W$). The shifting of modes of the dual-mode MPPT between 1 and 2 are shown in "mode" evolution figure, where $mode = 0$ indicates the curve tracing operation. However, the current GMPP conductance value is 0.28, consequently the periodic scanning process is activated. At $t = 6.5s$, the scan shows no irradiation variation. The PSCs vary from pattern 2 to pattern 3 at $t = 8s$. Since the criterion (4) is not met, this change can not be considered before the next scan. The search process at $t = 9s$ reveals the new PSC profile allowing the operation at the GMPP with power equal to $362W$.

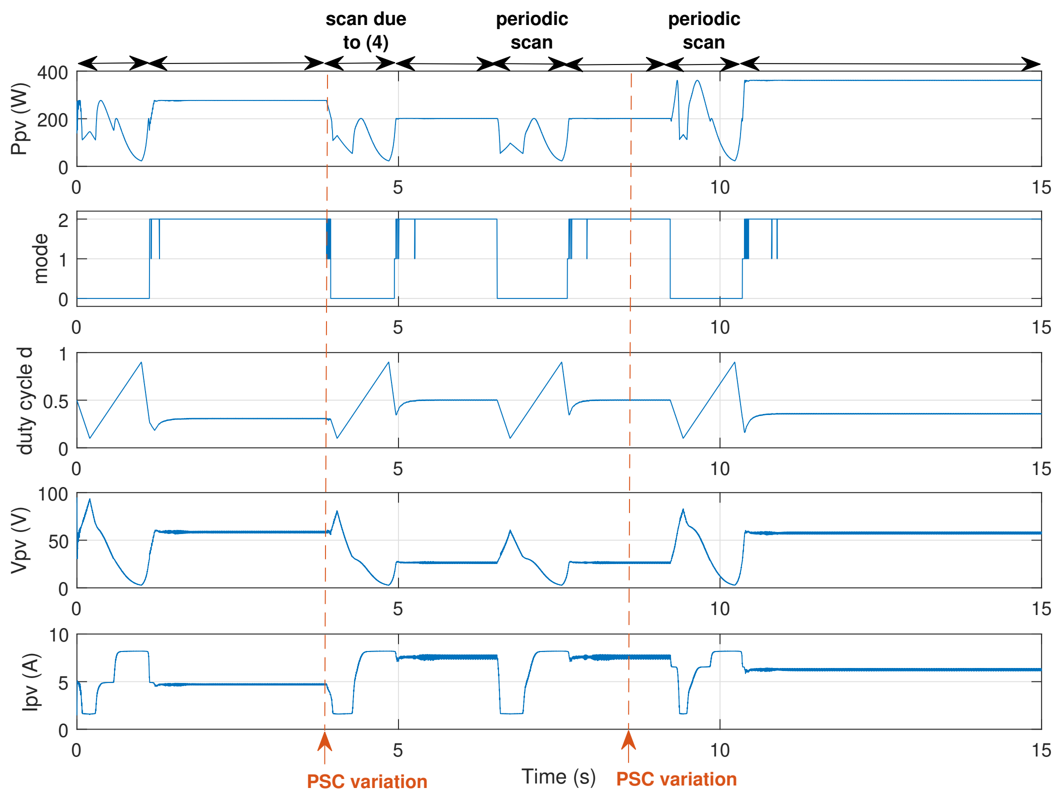

Fig. 5: The evolution of the system's outputs under varying PSC

The evolution of the duty cycle mainly controlling the converter also presented in Fig. 5 explicitly shows the variation of its value during the curve tracing and the smoothing transition phases between the two subprograms. Besides, the impact of this forced variation on the voltage and the current at the output of the PV array is displayed.

Moreover, in order to verify and quantify the performance of the proposed technique, it is compared to a similar method only eliminating the criterion Q originally used as a watchdog for the critical partial shading conditions. The two algorithms are tested under the scenario previously described highlighting a critical case where the variation from pattern 2 to pattern 3 can be undetected. Fig. 6 shows the variation of power of both methods. The proposed algorithm with Q criteria power evolution is the one detailed before along with the different measurements. Nevertheless, removing the critical PSCs watchdog, the variation at $t = 8s$ goes under the radar as expected. The algorithm continues to operate at the local maximum point positioned to the leftmost of the P-V curve with $P_{PV} = 202W$ although the new global maximum point is in the middle with $P_{PV} = 362W$.

This loss of power can be quantified, so the energy gathered during this simulation is presented in Fig. 7. From the start till $t = 6.6s$, the energy harvested is exactly the same while going through two P-V curve scans due to power variation. At $t = 6.6s$, an unnecessary scan causes a light drop in energy for the proposed method. Nonetheless, this energy loss is compensated from $t = 10.6s$ instant. The choice of irradiation variation instant and periodic scan duration surely impact the energy yield. This work presented an adapted time scale scenario similar to a lifelike irradiation variation profile. Furthermore, it quantified the power loss caused by an unnecessary scan and the one engendered by not tracking the global maximum power point. So depending on the application and PV placement, the user can decide which criteria to prioritize and adapt the parameters (timer's duration, Q_{nom} value, etc) accordingly.

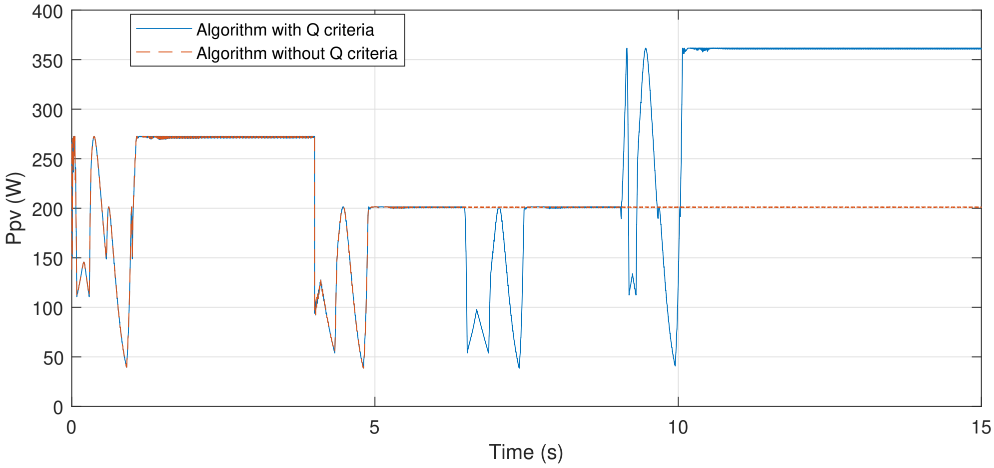

Fig. 6: The variation of power comparison for algorithms with/without Q criteria

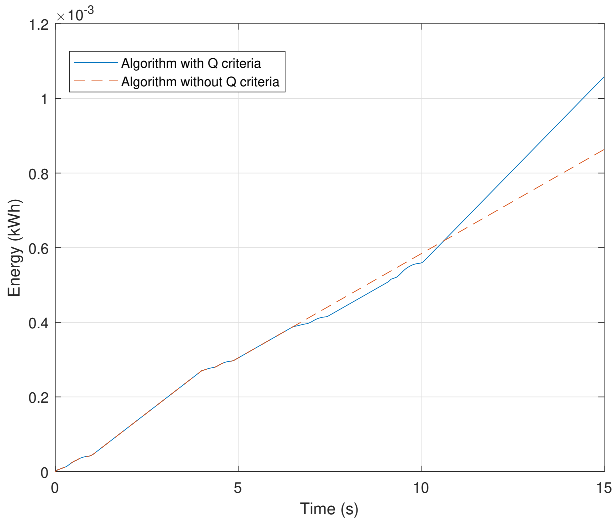

Fig. 7: The energy harvested comparison for algorithms with/without Q criteria

Conclusion

Optimizing the operational performance of GMPPT techniques during uniform or non-uniform irradiation variation has become a major challenge. PSC detection techniques are facing many obstacles. The proposed GMPPT method suggests a PSD while encountering the critical PSC variation cases. The critical PSCs are introduced in this paper and their occurrence is justified. Then, the proposed algorithm, controlling a DC/DC quadratic boost converter to extract maximum power from a PV array, is presented. It alternates non-regularly between two sub-programs: a novel MPPT algorithm and a rapid scanning procedure. The aperiodic scan-dual-mode method ensures operating at the GMPP even in critical PSC while reducing the transition to the scan as rarely as possible. The global PV system proved great performance in the newly introduced critical cases and notable superiority in all varying PSC, in a Simulink/MATLAB environment.

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