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A New Technique for Tracking the Global Maximum Power Point of PV Arrays Operating Under Partial-Shading Conditions

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Abstract— **The power-voltage characteristic of Photovoltaic (PV) arrays operating under partial shading conditions exhibits multiple local Maximum Power Points (MPPs). In this paper, a new method for tracking the global MPP is presented, which is based on controlling a DC/DC converter connected at the PV array output, such that it behaves as a constant input-power load. The proposed method has the advantage that it can be applied in either stand-alone or grid-connected PV systems comprising PV arrays with unknown electrical characteristics and does not require knowledge about the PV modules configuration within the PV array. The experimental results verify that the proposed global MPP method guarantees convergence to the global maximum power point under any partial shading conditions. Compared to past-proposed methods, the global MPPT process is accomplished after much less PV array power perturbation steps.**

Index Terms— **DC-DC power converters, Maximum power point tracking, Microcontrollers, Photovoltaic systems.**

I. INTRODUCTION

In typical Photovoltaic (PV) installations, PV arrays are formed by connecting multiple PV modules in various configurations (i.e. series, parallel, series-parallel etc.) [1]. A bypass diode [2] or bypass switch [3] is connected in parallel with each PV module for protecting the solar cells against efficiency degradation and hot-spot failure effects. Under uniform solar irradiation conditions among the individual PV modules, the power-voltage characteristic of the PV array exhibits a unique operating point where the PV generated power is maximized (Maximum Power Point, MPP). Many Maximum Power Point Tracking (MPPT) methods have been developed in the past in order to operate the PV array at the MPP point [4], enabling the maximization of the PV energy production under the continuously changing solar irradiation and ambient temperature conditions.

However, in the case that one or more of the PV modules comprising the PV array are shaded (e.g. due to dust, shading from surrounding buildings, trees or poles, non-uniform solar irradiation incidence on contoured flexible PV arrays [5] in portable and building integrated PV applications etc.), then the

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power-voltage characteristic of the PV array exhibits multiple local maxima and only one of them corresponds to the global maximum power point. Examples of the power-voltage (P-V) characteristics of a PV array operating under uniform and non-uniform solar irradiation conditions are depicted in Fig. 1. The PV array output power at the global MPP is lower than the sum of the maximum available power levels that the individual PV modules are able to provide [6]. As analyzed in [7], under practical operating conditions the location and magnitude of the local and global MPPs depend on the stochastically varying shading pattern area and geometry as well as the configuration of the PV modules within the PV array.

The connection of PV cells and modules in parallel, proposed in [8] in order to avoid the effect of partial shading, is applicable only in low-power PV systems (e.g. for portable applications). Using the distributed MPPT (DMPPT) technique, a DC/DC power converter with MPPT controller is incorporated at each PV module of the PV array [6, 9], thus increasing the total available MPP power of the PV array. However, the entire PV array is usually connected to a central power electronic converter in order to reduce the PV system cost and implementation complexity [1].

Under partial shading conditions, the conventional MPPT techniques fail to guarantee successful tracking of the global MPP [10], resulting in significant reduction of both the generated power and the PV energy production system reliability [11]. According to measurements performed under real operating conditions of PV systems, the power loss due to the MPPT algorithm convergence to a local (instead of the global) MPP may be up to 70% [11]. In the "1000 rooftop PV systems" program implemented in Germany, it has been recorded that the operation of the 41% of the installed PV systems had been affected by shading, with energy losses of
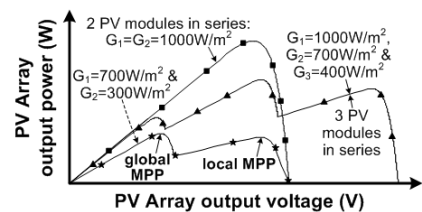

Fig. 1. Examples of the power-voltage characteristics of a PV array composed of identical series-connected PV modules with bypass diodes for different irradiations.

the order of 10% [12].

The reconfiguration of the connections between the individual PV modules comprising the PV array, using a matrix of power switches, has been proposed in [13]. The target of this reconfiguration is to form the parallel-connected strings comprising the PV array such that they consist of PV modules operating under similar solar irradiation conditions. Using this method both the PV energy production system complexity and cost are significantly increased.

The application of the global MPPT algorithm proposed in [14] requires the characterization of the PV source after each partial shading topology has been established. In [15], the equations for the calculation of the local MPPs of partially shaded multi-crystalline silicon PV modules are provided. In [16], the global MPP is tracked by scanning the P-V curve based on information of the PV modules open-circuit voltage and their configuration on the PV array. The global MPPT methods presented in [17] and [18] are based on the measurements of the PV array open-circuit voltage and solar irradiation or short-circuit current, respectively. The sequential extremum seeking control algorithm and the Incremental Conductance-based MPPT method with step-size variation are applied in [19] and [20], respectively. A common drawback of these methods is that they require knowledge of the electrical characteristics of the PV modules and/or their configuration within the PV array. Thus, they are not really applicable for the development of commercial PV power processing interfaces, where both the PV array configuration and the PV modules electrical characteristics applied by the end-user are generally unknown. Additionally, the accuracy of the calculations is affected by the PV modules electrical parameters deviation due to aging. The use of specialized sensors (e.g. for the measurement of solar irradiation) increases the PV system cost, while on the other hand during the measurement of the PV array open-circuit voltage or short-circuit current the PV energy production is suspended.

In [21], a radial basis function and a three layered feed-forward neural network are used to track the global MPP, having the disadvantage that the MPPT control system implementation complexity is highly increased. Additionally, considerable computational efforts are required during the neural network training in order to ensure that the global MPPT process will be performed reliable and accurate under any shading conditions.

The MPPT algorithm based on a Fibonacci sequence [22] does not guarantee convergence to the global maximum power point. The Particle Swarm Optimization (PSO) [23], Genetic Algorithms (GAs) [24] and Differential Evolution (DE) [25] global MPPT approaches and the stochastic algorithm based on the chaos search theory, which is presented in [26], exhibit significant algorithmic complexity, which increases the implementation cost of the global MPPT control system.

The detection of local MPPs using a periodic scan sequence of the P-V curve is frequently employed in commercially available PV power conditioning devices [27]. Due to the long time required for the completion of this process, the PV
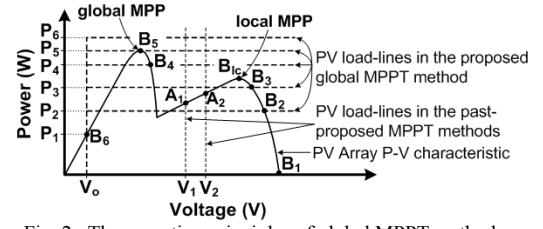

Fig. 2. The operating principles of global MPPT methods.

energy production is reduced. A global MPPT scheme based on the DIviding RECTangles (DIRECT) optimization algorithm is proposed in [28], having the advantage of avoiding the computation of the P-V function gradient. However, it is not guaranteed that under any partial shading conditions the convergence to the global maximum power point will be achieved in fewer steps than an exhaustive search procedure scanning the entire P-V curve.

The algorithmic complexity and tracking inefficiency of the methods described above arise because these methods are based on searching for the global MPP by iteratively controlling the operating voltage of the PV array load according to the corresponding MPPT algorithm. As illustrated in Fig. 2, the resulting operating point of the PV array lies on the intersection of the PV array and load power-voltage characteristics (e.g. points A_1 and A_2). Thus, the past-proposed algorithms are unable to guarantee the discrimination between local and global MPPs, unless the PV array output power is measured at a large number of operating points, spread over the entire voltage range of the PV array.

In this paper, a new method for tracking the global maximum power point of PV arrays operating under partial shading conditions, in either stand-alone or grid-connected PV systems, is presented. The PV array is connected to a DC/DC power converter, which is controlled by a microcontroller-based control unit. Initially, the power converter is controlled to operate as an adjustable constant input-power load. With reference to the power-voltage characteristics depicted in Fig. 2, starting from the PV array open-circuit condition (point B_1), the DC/DC converter is controlled to draw a successively higher amount of power. Hence, the PV array operating point is progressively moved towards higher output power levels (points B_1, B_2, B_3, B_4 and B_5). It is observed that using this process, the proposed algorithm avoids getting trapped in the local MPP (point B_{lc} in Fig. 2) and successfully detects the existence of the PV array operating points B_4 and B_5, which provide higher output power compared to the local MPP, without performing a PV-curve scanning procedure over a wide voltage range. This process is continued until convergence to point B_6 is detected, where the PV array output power increment is inhibited. This condition indicates that the previous PV array operating point (i.e. B_5 in Fig. 2) provides the maximum possible PV array output power, thus corresponding to the global MPP. Then, the DC/DC converter is controlled such that the PV array output voltage is regulated

to the global MPP point (B_5) detected in the previous phase of the algorithm. The experimental results presented in this paper verify that using this method enables the successful detection of the global MPP irrespectively of the number of local MPPs exhibited by the PV array power-voltage characteristic and their location relative to the global MPP. The global MPPT detection procedure described above is executed periodically (e.g. every 1-15 min). Then, the Perturb and Observe (P&O) MPPT process is applied in order to continuously track the short-term variations of the previously detected global MPP. According to [27], the iterative application of a PV-curve scan sequence with a 15 min scan interval, results in a less than 0.06% maximum energy loss on un-shaded arrays. As it will be demonstrated in the experimental results, the proposed global MPPT process is less time-consuming than the PV-curve scanning method. Thus, the periodic execution of the proposed global MPPT process does not result in significant energy loss in the case that the PV array is actually un-shaded. The P&O MPPT algorithm has been selected because of its implementation simplicity, flexibility and robustness [29]. However, any of the past-proposed MPPT algorithms [4] can also be applied in order to conform with specific PV system design specifications. Compared to the past-proposed global MPPT techniques, the method presented in this paper has the advantage that it does not require knowledge of the electrical characteristics of the PV modules and their configuration within the PV array. In the following sections of this paper the proposed global MPPT system is first analyzed in details and then validated by experimental results.

II. THE PROPOSED GLOBAL MPPT SYSTEM

A detailed diagram of the proposed global MPPT system is depicted in Fig. 3. Depending on the PV system application domain, a Buck-type DC/DC power converter is used to interface the PV array output power to either a battery bank or a DC/AC inverter connected to the electric grid [30, 31]. Both of these alternative types of DC/DC converter load are represented in Fig. 3 by the voltage source V_o. The inductance of the cable connecting the PV array to the DC/DC converter,
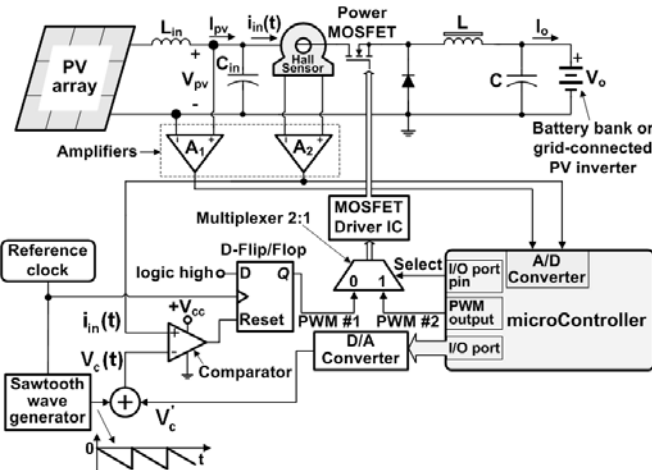

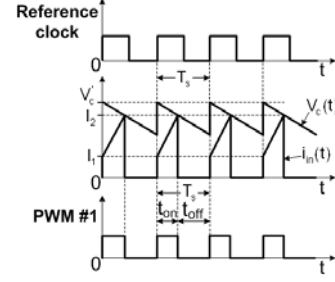Fig. 3. A detailed block diagram of the proposed global MPPT system.

Fig. 4. The principal waveforms of the proposed global MPPT system.

L_{in}, is considered for stability analysis purposes, as discussed below. The inductor, L, and the input and output filter capacitor values, C_{in} and C, respectively, are calculated as described in [32] such that the DC/DC converter operates in continuous conduction mode and, simultaneously, the input and output voltage ripple factors are reduced to an acceptable limit. The PV array voltage is measured using an operational amplifier-based differential amplifier and the DC/DC converter input current is measured with a Hall-effect-based current sensor. The proposed global MPPT procedure is performed in three consecutive phases; the constant input-power, PV array voltage regulation and P&O stage, respectively. In order to execute these processes, the DC/DC power converter is controlled using either the "PWM #1" or the "PWM #2" control signals depicted in Fig. 3, which are produced as analyzed in the following.

A. DC/DC converter constant input-power mode

In this section, the DC/DC converter operation and control, such that it behaves as an adjustable constant input-power load, is presented. The operation of the DC/DC converter in this operating mode constitutes the basis for the detection of the PV array global MPP, according to the proposed global MPPT control algorithm.

The input-output voltage relationship of a Buck-type DC/DC converter is the following:

$$V_o = D \cdot V_{pv} = \frac{t_{on}}{T_s} \cdot V_{pv} \tag{1}$$

where V_{pv} and V_o (V) are the DC/DC converter input and output voltage levels, respectively, D is the converter duty cycle ($0 \le D \le 1$), T_s is the switching period and t_{on} is the ON time of the power MOSFET PWM control signal.

The "PWM #1" control signal, depicted in Fig. 3, is produced by comparing the instantaneous value of the DC/DC converter input current, $i_{in}(t)$ with the control signal $V_c(t)$ generated by the control unit. The corresponding waveforms are plotted in Fig. 4. The average value of $i_{in}(t)$ is equal to the PV array DC output current, I_{pv} (A) and it is given by:

$$I_{pv} = \frac{1}{T_s} \cdot \int_0^{t_{on}} \left(I_1 + \frac{V_{pv} - V_o}{L} t \right) dt = \frac{1}{T_s} I_1 t_{on} + \frac{1}{T_s} \cdot \frac{V_{pv} - V_o}{L} \cdot \frac{t_{on}^2}{2} \tag{2}$$

Since $i_{in}(t_{on}) = V_c(t_{on})$, the value of I_1 in (2) is calculated

using (1), as follows:

$$I_1 + \frac{V_{pv} - V_o}{L} t_{on} = I_1 + \frac{V_o}{L}(T_s - t_{on}) = V_c(t_{on}) = I_2 \quad \Rightarrow$$

$$I_1 = V_c(t_{on}) - \frac{V_o}{L}(T_s - t_{on}) \tag{3}$$

Combining (2) and (3), the DC/DC converter average input power, P_{pv} (W), is calculated using the following equation:

$$P_{pv} = V_{pv} I_{pv} = V_c(t_{on}) V_o - \frac{V_o^2 T_s}{2L} + \frac{V_o^2 t_{on}}{2L} \tag{4}$$

In the proposed method, the values of $V_c(t)$ and V_c' are selected such that $V_c(t) = V_c' - \frac{V_o}{2L} t$, thus resulting in:

$$P_{pv} = V_c' V_o - \frac{V_o^2 T_s}{2L} \tag{5}$$

where V_c' is a DC control signal of adjustable amplitude, produced by the control unit according to the global MPPT algorithm analyzed in the next section.

The DC/DC converter output voltage, V_o, depends on either the slowly-changing battery state of charge (in stand-alone applications) or the electric-grid voltage (in grid-connected PV systems) and remains approximately constant during the consecutive steps of the global MPPT process. Since the values of T_s and L are also constant, it is concluded from (1) and (5) that for $V_{pv} \geq V_o$ the DC/DC converter input power can be regulated to the desired level by adjusting the amplitude of the V_c' control signal (constant input-power mode of operation).

The current-voltage characteristics of the PV array and DC/DC converter operating under partial-shading and constant-input-power conditions, respectively, are depicted in Fig. 5. The points of intersection (i.e. points A, B, C etc. in Fig. 5) define the equilibrium operating points of the interconnected PV array-DC/DC converter system. Practically the cable inductance, L_{in}, is negligible. Thus, according to the stability analysis presented in [33], which has been performed for a PV array connected to a constant-power load (e.g. a switching power converter with regulated output voltage) in a spacecraft power processing system, the points A, C, E and F in Fig. 5 are stable, while points B and D are unstable. The points A, C, E and F in Fig. 5 correspond to the points B_1 - B_6 and B_{lc} of the P-V curve depicted in Fig. 2. In the proposed

method, the global MPP is tracked by controlling the DC/DC such that it behaves as a constant input-power load and simultaneously the PV array operates at the stable operating points A, C, E and F, according to the algorithm analyzed next.

B. The Global Maximum Power Point Tracking Algorithm

A flow-chart of the proposed global MPPT control algorithm is shown in Fig. 6. Initially, the global MPPT process is performed in order to detect the position of the global maximum power point of the PV array. During that phase of the proposed algorithm, the power converter control method is set such that the power converter operates as an adjustable constant input-power load, as analyzed in the previous section. The power drawn by the DC/DC converter (i.e. the PV array output power) is iteratively increased by appropriately adjusting the amplitude of the V_c' control signal output by the D/A converter, as follows:

$$V_c'(k) = V_c'(k-1) + \Delta V_c' \tag{6}$$

where $V_c'(k)$, $V_c'(k-1)$ are the V_c' signal values at steps k and $k-1$, respectively [initially $V_c'(0) = 0$] and $\Delta V_c'$ is the constant perturbation applied.

Increasing the value of $\Delta V_c'$ in (6) results in a reduction of the time required to detect the PV array global MPP, but also to reduce the ability of the algorithm to discriminate local and global MPPs of similar power levels.

At each step, the PV array operating voltage is measured and stored in the microcontroller memory. This process is repeated until the operating point of the interconnected PV array-DC/DC converter system moves to point B_6 depicted in Fig. 2, where the PV array output power increment is inhibited. This condition indicates that the PV array output power measured during the previous step of the algorithm corresponds to the global MPP. Then, the DC/DC converter duty cycle is iteratively reduced until the PV array output voltage is regulated to the global MPP. Only the PV array output voltage is measured in order to perform this process.
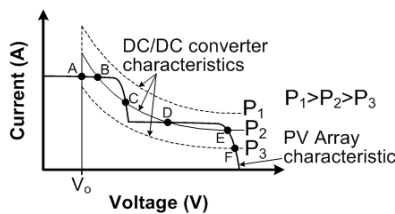

Fig. 5. The current-voltage characteristics of the PV array and the DC/DC converter operating under partial shading and constant input power conditions, respectively.
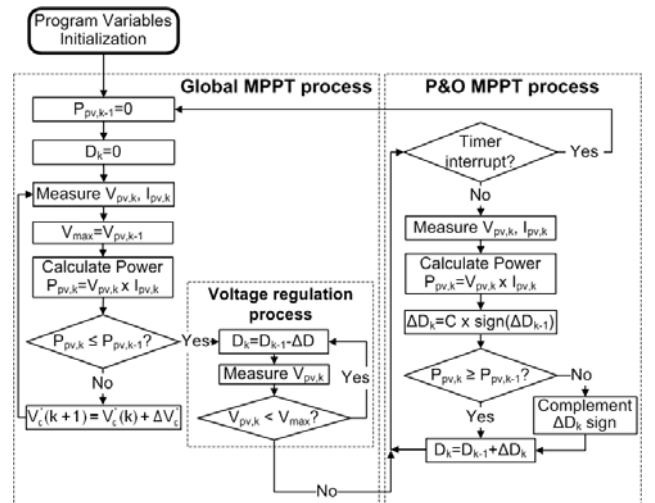

Fig. 6. Flow-chart of the proposed global MPPT control algorithm.

The procedure presented above is applied periodically (e.g. 1-15 min) for detecting the position of the global MPP of the PV array. Then, the P&O MPPT algorithm is executed in order to maintain operation at the previously detected global MPP during the short-term variations of solar irradiation and ambient temperature conditions.

During the P&O MPPT process, the DC/DC converter average input power is calculated by measuring the PV array output voltage and current. The resulting value is compared with the input power measured during the previous iteration of the algorithm. According to the result of the comparison, the duty cycle of the "PWM #2" DC/DC converter PWM control signal, depicted in Fig. 3, is modified as follows:

$$D_k = D_{k-1} + \Delta D_k$$
$$\Delta D_k = C \cdot sign(\Delta D_{k-1}) \cdot sign(P_{pv,k} - P_{pv,k-1}) \qquad (7)$$

where ΔD_k is the duty cycle change at step k, $P_{pv,k}$ and $P_{pv,k-1}$ are the PV array output power levels at steps k and $k-1$, respectively, C is a constant determining the speed and accuracy of convergence to the MPP point and the function $sign(x)$ is defined as:

$$sign(x) = 1, \quad if\ x \geq 0$$
$$sign(x) = -1, \quad if\ x < 0 \qquad (8)$$

The duty cycle is changed continuously according to the P&O algorithm, resulting in steady-state operation around the global MPP. A method for the optimal selection of the parameter C in (7) is described in [29].

III. EXPERIMENTAL RESULTS

A laboratory-prototype global MPPT system operating according to the proposed methodology has been developed and tested under outdoor conditions. The control unit of the proposed global MPPT system, which is illustrated in Fig. 3, has been built around the Atmel AVR ATMEGA8535 microcontroller, which features a 10-bit, 8-channel, A/D converter and on-chip 8-bit PWM outputs. The switching frequency of the "PWM #2" control signal has been set to 31.25 kHz. The PV array which has been used consists of three PV modules connected in series with a bypass diode in parallel with each module. The MPP power and voltage ratings of each PV module under Standard Test Conditions (STC) are 5 W and 17.82 V, respectively. For performance validation purposes, the Buck-type power converter output has been connected to a 12 V / 7 Ah lead-acid battery. Also, the PV modules comprising the PV array were installed at different tilt angles such that they receive unequal amounts of solar irradiation. Thus, the resulting power-voltage characteristic of the PV array exhibits both local and global MPPs.

Initially, the PV modules were installed such that the global MPP is located at a higher voltage compared to the local MPPs (test case #1). The corresponding power-voltage characteristic of the PV array was experimentally measured using a PV-curve scan process and it is plotted in Fig. 7(a).

Then, the proposed global MPPT method was applied. The experimentally measured operating points of the PV array during the execution of the proposed global MPPT process (i.e. points P_1 - P_{12}) are also indicated in Fig. 7(a). The minimum possible operating voltage of the PV array is 11 V, since a discharged battery has been connected at the DC/DC converter output terminals. The global MPP detection process was initiated, setting the PV array in an open-circuit operating condition (point P_1). By progressively increasing the value of the control signal V_c', the DC/DC converter was controlled such that it draws an increasing amount of power, thus causing the successive movement of the PV array operating points in the trajectory $P_1 \rightarrow P_2 \rightarrow P_3 \rightarrow P_4 \rightarrow P_5 \rightarrow P_6$. At point P_6 the next increment of the DC/DC converter input power moved the PV array operating point at P_7 (11 V, 3.03 W). The resulting reduction of the PV array output power was sensed by the microcontroller-based control unit, provoking the DC/DC converter operation in the voltage regulation mode. Thus, the DC/DC converter PWM control signal duty cycle was iteratively reduced until the PV array operating point was restored at point P_{12} (52.9 V, 7.44 W), where the highest PV output power was measured during the previous phase of the algorithm, through the trajectory $P_7 \rightarrow P_8 \rightarrow P_9 \rightarrow P_{10} \rightarrow P_{11} \rightarrow \rightarrow P_{12}$. Then, the execution of the P&O MPPT algorithm was initiated, resulting in a continuous oscillation of the PV array operating point around the previously detected global MPP (i.e. point P_{12}). During the P&O MPPT process, the maximum deviation of the PV array operating power from the global MPP has been experimentally measured to be equal to 0.43 %.

In order to validate that the proposed global MPPT method is equally efficient, irrespectively of the relative position of the local and global MPPs, the PV modules were also installed
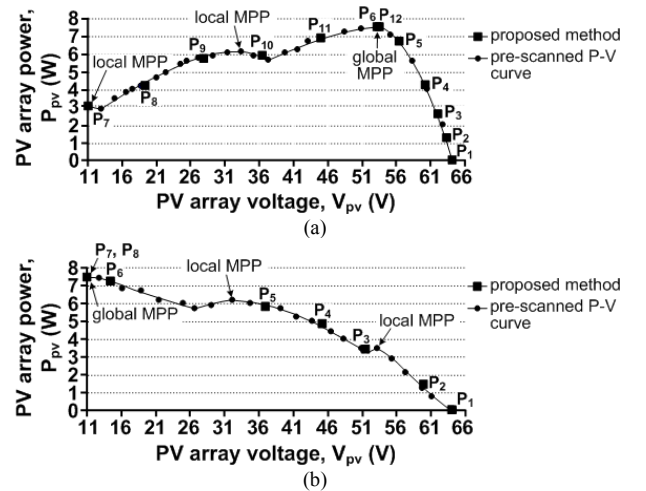

Fig. 7. The experimentally measured power-voltage characteristic of the PV array and the PV array operating points during the operation of the proposed global MPPT system, in case that the global MPP is located at: (a) higher voltage (test case #1) and (b) lower voltage (test case #2), compared to the local MPPs.

	Proposed algorithm	PV-curve scan	Particle Swarm Optimization (PSO)	Differential Evolution (DE)
Test case #1	12	50	33	2020
Test case #2	8	50	27	2020

such that the global MPP is located at a lower voltage compared to the local MPPs (test case #2). The resulting power-voltage characteristic of the PV array was experimentally measured using a PV-curve scan process and it is illustrated in Fig. 7(b). Then, the proposed global MPPT algorithm was executed. The experimentally measured operating points of the PV array during the execution of the proposed global MPPT process (i.e. points P_1 - P_8) are also depicted in Fig. 7(b). During the global MPP detection phase of the proposed algorithm, the PV array operating point is continuously displaced, following the sequence $P_1 \rightarrow P_2 \rightarrow P_3 \rightarrow P_4 \rightarrow P_5 \rightarrow P_6 \rightarrow P_7$. In the test case presented in Fig. 7(b), the global MPP is located at the minimum possible operating voltage of the PV array (i.e. 11 V). Thus, at P_7 (11 V, 7.45 W) the next increment of the $V_c^{'}$ control signal does not alter the PV array operating conditions, indicating that the resulting point, P_8 (11 V, 7.45 W), is the global MPP. During the voltage-regulation mode initiated next, the PV array operating point was held at the global MPP point detected at the previous step (i.e. point P_8). Then, the P&O MPPT process was performed in order to track the short-term variations of the global MPP. Due to the oscillations inherent in the P&O MPPT process, the maximum deviation of the PV array operating power from the global MPP in this test case has been experimentally measured to be equal to 0.08%.

In both of the test cases analyzed above, the proposed global MPPT algorithm successfully avoided getting trapped in local optima and achieved convergence to the global maximum power point of the PV array. The microcontroller-based control unit of the laboratory-prototype global MPPT system was also programmed for tracking the PV array global MPP in the two test cases described above according to the PV-curve scan sequence [27], Particle Swarm Optimization (PSO) [23] and Differential Evolution (DE) [25] methods. Only the "PWM #2" control signal (Fig. 3) has been used for that purpose. In the PV-curve scan sequence algorithm, the duty-cycle perturbation step has been set equal to that of the proposed algorithm [parameter C in (7)]. The values of the parameters affecting the operation of the PSO and DE algorithms (e.g. number of agents in the PSO method, termination criterion etc.) have been set as described in [23] and [25], respectively. All algorithms successfully detected the position of the global MPP. The experimentally measured numbers of the PV array power perturbation steps required by each algorithm in order to derive the global MPP are given in Table I. It is observed that compared to past-proposed

methods, using the algorithm presented will result in a much faster convergence to the global MPP.

IV. CONCLUSION

The detection of global MPP is indispensable in order to maximize the PV system energy production in the case of PV array partial shading. In this paper, a new method has been presented for tracking the global MPP of PV arrays in either stand-alone or grid-connected PV systems, which is based on controlling the DC/DC power converter connected at the PV array output such that it behaves as a constant input-power load. Compared to the past-proposed global MPPT techniques, the method proposed in this paper has the advantage that it can be applied in PV arrays with unknown electrical characteristics and does not require knowledge of the PV modules configuration within the PV array. The experimental results verify that the proposed method guarantees convergence to the global MPP under any partial shading conditions. Additionally, the global MPPT process is accomplished with significantly less PV array power perturbation steps than those obtained using past-proposed techniques. The proposed method can easily be incorporated into any existing MPPT control system in both high nominal-power-rating PV systems and low-power energy harvesting applications.

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