MPPT Method for PV Systems Under Partially Shaded Conditions by Approximating $I–V$ Curve

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Abstract—Partially shaded (PS) photovoltaic (PV) arrays have multiple peaks at their $P–V$ characteristic. Although conventional maximum power point tracking (MPPT) algorithms are successful when PV arrays are under uniform irradiance conditions (UICs), their tracking speeds are low and may fail to track global maximum power point (GMPP) for PS arrays. Several MPPT algorithms have been proposed for PS arrays. Most of them require numerous samplings which decreases MPPT speed and increases energy loss. The proposed method in this paper gets the GMPP deterministically and very fast. It intelligently takes some samples from the array’s $P–V$ curve and divides the search voltage range into small subregions. Then, it approximates the $I–V$ curve of each subregion with a simple curve, and accordingly estimates an upper limit for the array power in that subregion. Next, by comparing the measured real power values with the estimated upper limits, the search region of GMPP is limited, and based on some defined criteria, the vicinity of GMPP is determined. Simulation and experimental results and comparisons are presented to highlight the performance and superiority of the proposed approach.

Index Terms—Current–voltage ($I–V$) characteristic, maximum power point tracker (MPPT), partially shaded (PS) condition, photovoltaic (PV) systems.

I. INTRODUCTION

PHOTOVOLTAIC (PV) power systems have been commercialized in many countries due to their long-term advantages. PV arrays are the fundamental elements of the PV systems, in which there is a nonlinear relation between its voltage and current, and only in one operating voltage, maximum power is generated which is called maximum power point (MPP). MPP will vary as the environmental conditions change. Hence, finding this optimal point to extract maximum power from a PV system in all environmental conditions is one of the main issues in PV applications.

For a PV array under uniform irradiance condition (UIC), there is only one peak (MPP) in its $P–V$ curve, and conventional MPPT techniques, such as Hill climbing, perturb and observe (P&O), and incremental conductance can track it efficiently [1]. Although these methods are quite simple in implementation, they may fail for the arrays under partially shaded conditions (PSC). In PSCs, PV modules of an array do not receive equal solar irradiance, and the array $P–V$ characteristic may contain multiple peaks with different power values. In the most cases, PSCs are inevitable, especially in PV systems installed in urban areas or where low moving clouds are common [2]. Hence, analysis of PSC and mitigation of PSC effects have been interesting from research point of view [3]. Accordingly, numerous MPPT methods for PV systems under PSC have been presented [3]–[23]. In general, tracking methods are categorized into two overall groups. The first group involves hardware-based methods, such as those use different array reconfigurations, extra measurements [4]–[6], or different converter topologies [7]–[9]. On the other side, the second group is based on search algorithms which are realized by only modifying the control software in the present commercial power converters, and are preferable due to lower cost and complexity compared to hardware-based methods.

The presented method in [6] well detects the PS occurrence, calculates the number of peaks in $P–V$ curve, and predicts the locations of all MPPs by measuring the voltage of all PV modules. It also finds the global MPP (GMPP) correctly and has a good performance, but it needs a large number of sensors to satisfy the control goals. The presented MPPT method in [9] uses controllable current transformers in parallel with PV modules to regulate module currents and to track the GMPP. This method decreases the PS effect on the array power and has a good accuracy, but its implementation is complex and expensive.

Some papers in the literature have looked to MPPT problem as an optimization problem and have used several intelligent and heuristic algorithms, such as flashing fireflies [10], artificial bee colony [11], fuzzy-logic control [12], chaotic search [13], simulated annealing [14], grey wolf optimization technique [15], and particle swarm optimization [16] to find GMPP in PSCs. These methods, however, suffer from sharp fluctuations in the system dynamic (poor dynamic performance), complexity in implementation, and necessity to numerous samplings at different points of the $P–V$ characteristic, and low MPPT speed. In some cases, their success depends on the starting values which should be selected wisely to guarantee the convergence [14], [17].

The proposed method in [18] samples from the $P–V$ curve at $V = 0.8 V_{oc\mod}$ intervals. In the vicinity of those samples with $dP/dv < 0$, there is a peak which is tracked by P&O technique. Finally, by comparing all the tracked peaks, GMPP is determined. The proposed method in [19] assumes that the peaks of $P–V$ curve are located at the multiples of $0.8 V_{oc\mod}$ which is not necessarily true [3]. The presented method in [20],
uses the voltage step of \( VGSTEP = 0.5V_{oc-mod} \) to scan \( P-V \) curve for GMPP from minimum voltage towards maximum voltage while some steps are ignored smartly, and search region is limited. This method has good speed and performance, but it may not find GMPP in scanning with VGSTEP in some cases, the defect which has been observed in [19] and resolved in [18] by calling P&O in each sample. In [4], two other methods have been introduced. The presented search based method skips search of some voltage ranges based on the measured current of the array and the highest sampled power. This method has high accuracy, but it must scan a large part of the \( P-V \) curve with small steps which reduces the tracking speed significantly.

Ghasemi et al. [21] proposes a method that scans the PV array using ramp function instead of conventional step-like changes. Since transients of the array voltage are negligible and the sampling interval is eliminated, this approach has gained desired speed and better dynamic performance. The proposed method in [22] samples from the array voltage in multiples of 0.8 \( V_{oc-mod} \) and determines an upper bound for the array power in the vicinity of each sample. Then, it searches the vicinity of the samples which their upper bounds power is greater than the highest sampled power for the probable MPP. The proposed method in [23] samples from the array current in multiples of \( V_{oc-mod} \). Then, by comparing the measured currents against each other, the number of steps, their lengths, and their order in the current–voltage (\( I-V \)) curve are determined. When there is a step change in the \( I-V \) curve, it calls hill climbing algorithm to track those MPPs. Finally, by comparing the value of tracked MPPs, GMPP is determined.

Generally, a good MPPT algorithm should track the GMPP in all conditions and find it quickly to guarantee high efficiency. It should also have a simple implementation with a low computational burden. This paper proposes a new algorithm for finding the GMPP in all irradiance conditions. The proposed method takes some samples from the \( I-V \) curve, divides the voltage search region into small subregions and estimates an upper limit for array power in that subregion. Then, by comparing the highest sampled power with the estimated upper limits, the search region is limited. By continuing this procedure, the vicinity of GMPP is determined. Finally, the exact GMPP is tracked by the P&O algorithm.

The rest of the paper is organized as follows: Section II discusses the overall characteristics of PV arrays under PSC. Section III presents the structure of the proposed MPPT method. Detailed descriptions of the proposed method are presented in Section IV. Control of the dc/dc converter used in MPPT is explained in Section V. Operation of the proposed method is simulated in Section VI and compared with four most referenced methods in the literature. Experimental results and comparisons are presented in Section VII. Finally, conclusions of the paper are reported in Section VIII.

II. CHARACTERISTICS OF A PV ARRAY UNDER PSC

Overall schematic diagram of a PV system is shown in Fig. 1. PV array is the main element of a PV system which consists of PV modules. Besides, the dc/dc converter plays the main role in absorbing power from the PV array by controlling its voltage. The generated power can feed the dc load or battery, or it is delivered to ac grid by an inverter. In this paper, without loss of generality, and for the simplicity, it is supposed that the output of the dc/dc converter is connected to a constant dc source, e.g., a battery.

To analyze the behavior of PV arrays under PSC, at first, one has to evaluate its \( I-V \) relationship under UIC. For this purpose, among different models available in the literature for solar cells and PV modules, the single-diode model, which is shown in Fig. 2, is considered. Based on this model, the current (\( I \)) of a PV module is expressed as follows [21]:

\[
I = I_{pv} - I_o \left[ \exp \left( \frac{V + R_s I}{n q A V_T} \right) - 1 \right] - \frac{V + R_s I}{R_{sh}} \quad (1)
\]

where \( V_T = n k T / q, I_{pv} \) is the photo-generated current, \( I_o \) is the reverse saturation current, \( R_s \) is the series resistance, \( R_{sh} \) is the parallel resistance, \( A \) is the diode ideality factor, \( q \) is the electron charge, \( k \) is the Boltzmann’s constant, and \( T \) is the module temperature (in Kelvin).

The maximum current of a module is achieved when \( V = 0 \) and is known as short-circuit current (\( I_{sc-mod} \)). For voltages greater than the open \( I-V \) of a module (\( V_{oc-mod} \)), the current will be zero. To provide desired voltage and current levels, a PV array includes several parallel PV strings, where each string is a series connection of PV modules. In UIC, the MPPTs of the module and the array are achieved at \( V_{mpp-mod} = a V_{oc-mod} \) and \( V_{mpp-arr} = N_s V_{mpp-mod}, \) respectively; where \( a \) is a coefficient that depends on the module type, temperature and irradiance level (\( a \) is about 0.8), and \( N_s \) is the number of series modules in each string.

Under PSC, PV modules of the array receive different insolation levels (ILs) and generate different \( I_{pv} \), which results in hot-spots in the shaded modules and can damage to them [21]. To resolve this problem, a bypass diode is connected in parallel with each PV module [see Fig. 3(a)] which, in turn, causes multi MPP in \( P-V \) curve of the array. The general operation of a PV string under PSC and the corresponding \( I-V \) and \( P-V \) curves are shown in Fig. 3.

Finally, it is worthy to note that the positions of peaks in the \( P-V \) curve of a partially shaded array are not specific, and depend on the shading pattern. Nevertheless, it can be shown that all peaks stay at the following voltage range [4], [22]:

\[
V_{mpp-mod} < V < 0.9 V_{oc-arr} \quad (2)
\]
be estimated by

\[ P_{\text{up} \rightarrow k} = V_{k+1} I_k \]  

(3)

As the basic description of the proposed method, suppose that the voltage range (2) has been divided to \( n - 1 \) subregions by \( n \) samples from the array \(((V_1, I_1, P_1), \ldots, (V_n, I_n, P_n))\). Then, upper limits of the power at all subregions are estimated using (3) as \( P_{\text{up} \rightarrow k} \) (\( k = 1, 2, \ldots, n - 1 \)). Afterwards, the maximum value of all sampled (measured) powers, i.e., \( \max(P_1, P_2, \ldots, P_n) \) which is called \( P_{\text{max} - s} \), is compared with all \( P_{\text{up} \rightarrow k} \). Certainly, in the subregions that \( P_{\text{up} \rightarrow k} \) is lower than \( P_{\text{max} - s} \), the GMPP is not in that subregion and it can be eliminated from the search region. In other words, the search area is limited to the subregions with \( P_{\text{up} \rightarrow k} \) greater than \( P_{\text{max} - s} \). Hereafter, these subregions are named candid subregions. With similar procedure and further intelligent samplings, search region becomes smaller gradually until the vicinity of GMPP is achieved.

Based on the presented explanations, the structure of the proposed method is established on three main parts consist of intelligent sampling, \( I-V \) curve approximation and search termination criterion. Accordingly, calculation of \( P_{\text{up} \rightarrow k} \) based on the modified approximation for the \( I-V \) curve and a criterion for termination of the search are proposed in the following, and the intelligent sampling procedure is explained in the next section.

A. Modified Approximation of PV Array’ \( I-V \) Curve

Approximating the \( I-V \) curve with the constant current curve is too conservative. It means that the resulted \( P_{\text{up} \rightarrow k} \) in the subregion \( k \) is much greater than the real probable peak power. This can increase the search time for getting GMPP. Hence, in the following, a modified approximation of the real \( I-V \) curve is proposed which is depicted in Fig. 4 and compared with constant current curve approximation. It is clear that since the new approximated curve is under the constant current curve, it yields smaller \( P_{\text{up} \rightarrow k} \).

The new approximated curve in the subregion \( k \) is summation of two curves. The first curve is a constant current curve with the value of \( I_{k+1} \). The second function is the \( I-V \) curve of a typical module \((I_{\text{T-M}}(V))\) with an specific \( V_{oc} \), called \( V_{oc-T-M} \) and an specific \( I_{sc} \), called \( I_{sc-T-M} \), similar to the one shown in Fig. 4. Therefore, the current of the approximated curve is as follows:

\[ I_{\text{pp}}(V) = I_{k+1} + I_{T-M}(V-V_k), \quad V_k < V < V_{k+1} \]  

(4)

The start and end points of the real and approximated curves are equal together, i.e., \((V_k, I_k)\) and \((V_{k+1}, I_{k+1})\). The maximum power of the approximated curve must be greater than the maximum power of the array (real curve) in the related subregion. It
can be shown that choosing $V_{oc-T-M}$ and $I_{sc-T-M}$ as (5), will satisfy the necessary condition

$$V_{oc-T-M} = V_{k+1} - V_k$$

$$I_{sc-T-M} = I_k - I_{k+1}$$ \hspace{1cm} (5)

Accordingly, the maximum power of the approximated curve ($P_{app-k}$) can be the upper limit for the array power in subregion $k$. Determination of $P_{app-k}$ is explained in the following.

First, let’s suppose that in Fig. 4, $V_k = 0$ and $I_{k+1} = 0$.

In this situation, the maximum power of the approximated $I-V$ curve will be at $V = V_{mpp-T-M}$, and it is equal to $V_{mpp-T-M} I_{mpp-T-M}$, where $V_{mpp-T-M}$ and $I_{mpp-T-M}$ are the current and voltage of the typical module [specified in (5)] at the MPP. By considering nonzero values for $V_k$ and $I_{k+1}$, MPP would be at $V = V_{mpp-T-M} + V_k$ or $V < V_{mpp-T-M} + V_k$ or $V > V_{mpp-T-M} + V_k$.

In the subregion $[V_k, V_{k+1}]$, the power of approximated curve is derived as follows:

$$P_{app} = V_{app} I_{app} = (V_k + V_T-M) (I_{k+1} + I_T-M)$$

$$= V_k I_{k+1} + V_k I_T-M + V_T-M I_{k+1} + V_T-M I_T-M$$ \hspace{1cm} (6)

where $I_T-M$ and $V_T-M$ are the current and voltage of that typical module. It is clear that

$$\max(P_{app}) \leq \max(V_k I_{k+1}) + \max(V_k I_T-M)$$

$$+ \max(V_T-M I_{k+1}) + \max(V_T-M I_T-M)$$

$$= V_k I_{k+1} + \max(V_k I_T-M) + \max(V_T-M I_{k+1})$$

$$+ V_{mpp-T-M} I_{mpp-T-M}$$ \hspace{1cm} (7)

Then, if MPP is at $V = V_{mpp-T-M} + V_k$, one can derive that

$$\max(P_{app}) = (V_k + V_{mpp-T-M}) (I_{k+1} + I_{mpp-T-M})$$ \hspace{1cm} (8)

If MPP is at $(V > V_{mpp-T-M} + V_k, I < I_{mpp-T-M} + I_{k+1})$, then the max of $(V_k I_T-M)$ in that subregion would be $V_k I_{mpp-T-M}$, and $\max(V_T-M I_{k+1})$ becomes equal to $(V_{k+1} - V_k) I_{k+1}$.

Therefore

$$\max(P_{app}) \leq V_k I_{k+1} + V_k I_{mpp-T-M} + (V_k+1 - V_k) I_{k+1}$$

$$+ V_{mpp-T-M} I_{mpp-T-M}$$

$$= V_{k+1} I_{k+1} + V_k I_{mpp-T-M} + V_{mpp-T-M} I_{mpp-T-M}$$

$$= V_{k+1} I_{k+1} + (V_k + V_{mpp-T-M}) I_{mpp-T-M}$$ \hspace{1cm} (9)

If MPP is at $(V < V_{mpp-T-M} + V_k, I > I_{mpp-T-M} + I_{k+1})$ then $\max(V_k I_T-M)$ in that subregion would be $V_k (I_k - I_{k+1})$, and $\max(V_T-M I_{k+1})$ gets equal to $V_{mpp-T-M} I_{k+1}$. Therefore

$$\max(P_{app}) \leq V_k I_{k+1} + V_k (I_k - I_{k+1}) + V_{mpp-T-M} I_{k+1}$$

$$+ V_{mpp-T-M} I_{mpp-T-M}$$

$$= V_k I_k + V_{mpp-T-M} I_{k+1} + V_{mpp-T-M} I_{mpp-T-M}$$

$$= V_k I_k + V_{mpp-T-M} (I_{k+1} + I_{mpp-T-M})$$ \hspace{1cm} (10)

Finally, by selecting $P_{up-k} = \max(P_{app})$ and considering (8)-(10), one can obtains

$$P_{up-k} = \max(P_{app})$$

$$\leq \max(V_k + V_{mpp-T-M} + I_{mpp-T-M}), V_{k+1} I_{k+1}$$

$$+ (V_k + V_{mpp-T-M})$$

$$\times I_{mpp-T-M}, V_k I_k + V_{mpp-T-M} (I_{k+1} + I_{mpp-T-M})$$ \hspace{1cm} (11)

where, the right term of (11) can be considered as $P_{up-k}$ in the related subregion.

It can be seen from (11) that the value of $P_{up-k}$ increases with the increase of $V_{mpp-T-M}$ and $I_{mpp-T-M}$. $V_{mpp-mod}$ and $I_{mpp-mod}$ of commercial modules are always smaller than $0.85 V_{occ-mod}$ and $0.95 I_{sc-mod}$, respectively. Therefore, $V_{mpp-T-M} = 0.85 V_{oc-T-M}$ and $I_{mpp-T-M} = 0.95 I_{sc-T-M}$, is used in (11) for all types of arrays and modules. Accordingly, the new estimation of (11) with the mentioned $V_{mpp-T-M}$ and $I_{mpp-T-M}$ is used for the estimation of $P_{up-k}$ instead of (3).

B. Search Termination

Based on the presented basic explanations about the proposed method, with further samplings from the array, candid subregions and search region become smaller gradually. Now, suppose that after some samplings, the voltage range $[V_L, V_U]$ is the smallest voltage range that the all candid subregions (defined previously) are in it. On the other hand, it has been shown that the minimum voltage interval between the MPPs in a PS array is 0.5 $V_{oc-mod}$ [20]. Hence, in a voltage range which its length is lower than $2 \times 0.5 V_{oc-mod}$, there is at most two MPPs. Accordingly, the sampling in the proposed method is continued until $\Delta V = V_U - V_L$ becomes lower than $2 \times 0.5 V_{oc-mod}$. Then, P&O algorithm is called to track the MPP, starting from $V_{max-s}$. Then, $P_{max-s}$ is updated again with the new obtained $P_{mpp}$ ($P_{max-s} = P_{mpp}$), and $V_L, V_U$, and $\Delta V$ are also updated. Afterwards, it is checked whether $V_U = V_{mpp + 0.5 V_{oc-mod}} < V_U$ & $V = V_{mpp - 0.5 V_{oc-mod}} > V_L$ or not. Since the maximum value of the new updated $\Delta V$ is $2 \times 0.5 V_{oc-mod}$, only one of the above conditions may be met. If none of them is satisfied, GMPPT is terminated, and GMPP would be equal to the MPP which was obtained previously. Otherwise the following is true.

1) If $V = V_{mpp} + 0.5 V_{oc-mod} < V_U$, a new sample is taken at $V = V_{mpp} + 0.5 V_{oc-mod}$, and the $P_{ap}$ of the new subregion $[V_{mpp} + 0.5 V_{oc-mod}, V_U]$ is calculated. If it is smaller than $P_{max-s}$, GMPPT is terminated and GMPP will be equal to the previous achieved MPP. Otherwise, there is a MPP at the vicinity of the last sample and is tracked by P&O algorithm starting from $V_U$. Then, the power of the new MPP is compared with the power at the previous MPP, and GMPP will be the largest one.

2) If $V = V_{mpp} - 0.5 V_{oc-mod} > V_L$, a new sample is taken at $V = (V_{mpp} - 0.5 V_{oc-mod})$, and the $P_{ap}$ of the new subregion $[V_L, V_{mpp} - 0.5 V_{oc-mod}]$ is calculated. If it is smaller than $P_{max-s}$, GMPPT is terminated and GMPP will be equal to the previous obtained MPP. Otherwise, there is a MPP at the vicinity of the last sample and is tracked by P&O algorithm starting from $V = V_L$. The power of the new MPP is compared with
the power at the previous MPP, and GMPP will be the largest one.

IV. PROPOSED GMPPT ALGORITHM

In the previous section, basic description of the proposed method was presented, and approximating the I–V curve of the PV array and search termination criterion as two main parts of the proposed method were explained. In this section, full explanation of the proposed algorithm is presented with an emphasis on other main part of the method which is intelligent sampling procedure.

Under PSC or change of PSC pattern, the array power changes abruptly. Therefore, the power difference between two consecutive samples \((\Delta P)\) can be compared against a certain critical value \(\Delta P_{\text{crit}}\). If \(\Delta P\) is higher than \(\Delta P_{\text{crit}}\), it is recognized as PSC occurrence or change in PSC pattern. More detail about determination of \(\Delta P_{\text{crit}}\) can be found in [18]. In this paper, this threshold is set to 5% of the nominal power. However, there are situations, especially in changing PS patterns, where no big change in the array power is observed. Therefore, some papers propose to trigger GMPPT method periodically to handle these situations [4]. Therefore, the proposed algorithm is triggered periodically or when a sudden change in the array power (bigger than \(\Delta P_{\text{crit}}\)) occurs. Finally, the proposed method works based on the following steps.

1) First sampling: The algorithm is started based on three samples from the array P–V curve. The first sample is the operating point of the array after PSC occurrence which is called \((V_{\text{op}}, P_{\text{op}})\). The second sample is \(V_{\text{up}} = V_{\text{oc–arr}}\) in which the current is zero. It must be noted that \(V_{\text{oc–arr}}\) is not constant and changes under different situations. In this paper, its maximum probable value is used. The mentioned two samples are known and no perturbation in the array voltage is needed to achieve them. The third sample is taken at \(V_{\text{low}} = V_{\text{mpp–mod}}\) which is the lower bound of the voltage range in (2). Briefly, the following samples are taken at first:

\[
\begin{align*}
V_1 &= V_{\text{mpp–mod}}, \quad P_1 \\
V_2 &= V_{\text{op}}, \quad P_2 = P_{\text{op}} \\
V_3 &= V_{\text{oc–arr}}, \quad P_3 = 0.
\end{align*}
\]  

(12)

Now, the voltage range in (2) is divided into two subregions consists of

\[
[[V_1 \ V_2] \quad [V_2 \ V_3]].
\]  

(13)

Until now, three samples (12) are considered which only \((V_1, P_1)\) is achieved by perturbation in the array voltage. However, during the tracking of GMPP, further samples may be needed. Hence, to generalize the following steps, it is supposed that \(n\) samples have been taken as follows:

\[
\{(V_1, P_1) \quad (V_2, P_2) \ldots (V_n, P_n)\}
\]  

(14)

which value of \(n\) and numbering of the samples change after any new sample as there is increasing trend from \(V_1\) until \(V_n\) that means \(V_k < V_{k+1}[k = 1 : n - 1]\).

2) In this step, \(\max(P_1, P_2, \ldots, P_n)\) is determined as highest sampled power \((P_{\text{max–s}})\), and \(P_{\text{up–k}}\) of all subregions \([V_k \ V_{k+1}] [k = 1 : n - 1]\) are calculated according to (11). It is worthy to note that if length of a subregion is small (for example less than 2 V) it is not needed to calculate its \(P_{\text{up–k}}\) as (11) and it is considered equal to maximum power of its adjacent samples.

3) Then, \(P_{\text{up–k}}\) are compared with \(P_{\text{max–s}}\).

a) In the subregions with \(P_{\text{up}}\) smaller than \(P_{\text{max–s}}\), the power of the array is certainly lower than \(P_{\text{max–s}}\), and the GMPP is not at those subregions. Therefore, they are eliminated from the search area.

b) Among the subregions with \(P_{\text{up}}\) greater than \(P_{\text{max–s}}\) (named candid subregions), the subregion which has the highest \(P_{\text{up}}\) is selected, and a new sample is taken at that subregion. Assuming that the corresponding subregion is \([V_m \ V_{m+1}]\), the new sample is taken at

\[
V_{s-m} = \max\left(\frac{P_{\text{max–s}}}{I_m}, \frac{V_m + V_{m+1}}{2}\right)
\]

(15)

where \(I_m\) is the current of the array at \(V_m\). Due to the descending slope of I–V curves, power of the array in the subregion \([V_m \ P_{\text{max–s}}/I_m]\) is certainly lower than \(P_{\text{max–s}}\), and this region is not needed to be searched for GMPP. There are situations that \(P_{\text{max–s}}/I_m\) is too close to \(V_m\), and sampling at this point and elimination of \([V_m \ P_{\text{max–s}}/I_m]\) is not useful; therefore, the mentioned sample is taken at (15) which is at least at the middle of the subregion. Furthermore, one has to note that if \(|V_{\text{up}} - V_{s-m}| < 0.5 V_{\text{oc–mod}},\) or distance between \(V_{s-m}\) with one of other samples was less than a small value (for example less than 1 V) no sample is taken at this subregion, and the mentioned subregion is replaced with the next subregion with the biggest \(P_{\text{up}}\), and the new sample is taken with the above-mentioned procedure.

4) It is clear that after each iteration and sampling, the search area for GMPP becomes smaller. Steps 2–4 are repeated over and over until the termination criteria described in previous section is met.

The complete flowchart of the algorithm is shown in Fig. 5.

V. CONTROL OF BOOST CONVERTER

The boost converter as the actuator of the MPPT algorithm should be controlled properly to have suitable dynamic performance. For the control part, there are two overall methods which one of them can be employed:

1) Open loop control: In this method, duty cycle of the converter is determined based on the output voltage of the converter \(V_o\) and the desired PV voltage, i.e.,

\[
D^* = 1 - \frac{V_{\text{ref}}}{V_o}.
\]

(16)
Fig. 5. Complete flowchart of the proposed algorithm.

Due to resonance manner between \( C_{\text{in}} \) and \( L \) of the converter and its low damping factor, and negative dynamic resistance of the PV array, the step response of the converter will have a large dynamics, especially for large steps of \( V_{\text{ref}} \). So it is not proposed for high performance applications.

2) Closed loop control: In this method, the closed loop system like the one in Fig. 6, where the PV voltage is fed back and compared with \( V_{\text{ref}} \), is used. Then, using a proportional-integral-derivative (PID) controller, the proper dynamic response is achieved. Also, in some cases, an extra feedback is taken form the inductor current and the dual loop control is applied. In this method, an extra current sensor is needed to measure the inductor current which increases the cost of the converter.

In this paper, the single voltage loop control is employed, and by a simple proportional-integral (PI) controller, proper dynamic responses are achieved.

VI. SIMULATION RESULTS

In this section, performance of the proposed global maximum power point tracking (GMPPT) method is evaluated using different simulations, and comparisons are done with four recent methods in the literature, i.e., [18], [20], [22], and [23]. The simulated system configuration is as shown in Fig. 1. The PV array is connected to a boost dc–dc converter which tracks the maximum power point. The output of the converter is connected to a constant voltage source. The parameters of the boost converter are listed in Table I.

The simulated array is a 3 × 9 array (three paralleled strings). The utilized PV module is YL70P-17b 1/2 PV type module which has two series submodules with corresponding bypass diodes. The electrical parameters of these submodules are given in Table II.

At first, the array is under UIC with irradiance level of \( I_{\text{L1}} = 0.9 \text{ kW/m}^2 \). During UIC, the array operates at MPP using P&O algorithm. Then, the first PSC occurs at \( t = 0.59 \text{ s} \), where the irradiance level of some modules drops to \( I_{\text{L2}} = 0.5 \text{ kW/m}^2 \). After sometime, at \( t = 1.47 \text{ s} \), the second PS pattern is applied. Finally, the irradiance level of all modules becomes equal to \( I_{\text{L2}} = 0.5 \text{ kW/m}^2 \) at \( t = 2.2 \text{ s} \), called UIC2. Fig. 7 shows the \( P-V \) and \( I-V \) curves of the array under the different mentioned irradiance patterns.

<table>
<thead>
<tr>
<th>TABLE I</th>
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<tr>
<td><strong>Boost Converter Parameters</strong></td>
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<td>Parameters</td>
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<tr>
<td>( L )</td>
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<tr>
<td>( C_{\text{in}} )</td>
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<tr>
<td>( I_{\text{L}} \max )</td>
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<td>Switching Frequency</td>
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<th>TABLE II</th>
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<tr>
<td><strong>Specifications of the YL70P-17b 1/2 PV Module in Standard Test Condition</strong></td>
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<td>Parameters</td>
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<tr>
<td>Open-circuit voltage (( V_{\text{oc-mod}} ))</td>
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<tr>
<td>Short-circuit current (( I_{\text{sc-mod}} ))</td>
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<tr>
<td>Voltage at ( P_{\text{max}} ) (( V_{\text{mp}} ))</td>
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<tr>
<td>Current at ( P_{\text{max}} ) (( I_{\text{mp}} ))</td>
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<td>Temperature coefficient of ( P_{\text{max}} )</td>
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<tr>
<td>Temperature coefficient of ( V_{\text{oc-mod}} )</td>
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<tr>
<td>Temperature coefficient of ( I_{\text{sc-mod}} )</td>
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</table>

Fig. 7. \( I-V \) and \( P-V \) characteristics of the simulated array under the specified irradiance patterns.
During UIC1, the operating point of the array is (78 V, 10.5 A, 841 W) achieved by P&O algorithm. It must be noted that based on the designed single loop control system with the parameters in Table 1, the settling time of the converter is obtained as 30 ms. Hence, the time interval between two consecutive samples from the array I–V curve (sample time) is chosen to be 35 ms. This sampling time will ensure that the system will reach the steady state condition, before the next perturbation. With the change of irradiance pattern to PSC1, a sudden power change occurs, and the operating point changes to (78 V, 6.1 A, 476 W). This is considered as the first sample. The second sample is taken at $V = V_{oc} - arr = 100$ V in which $(V, I, P) = (100$ V, 0 A, 0 W). The third sample is taken at $V = V_{mpp - mod} = 9$ V in which $(V, I, P) = (9$ V, 11.1 A, 100 W). Based on these three samples, $P_{max-s} = 476$ W. Now, there are two subregions, consists of $R_1 = [9, 78]$ and $R_2 = [78, 100]$ which their $P_{up}$s are calculated using (11) as 797 W and 560 W, respectively. Both of these values are greater than $P_{max-s} = 476$ W, where $P_{up}$ of $R_1$ is the largest one. Hence, the next sample is taken, in $R_1$, using (15) at $V = 43.5$ V in which $(V, I, P) = (43.5$ V, 11.08 A, 482 W). Now, $P_{max-s} = 482$ W, and we have three subregions $R_1 = [9, 43.5]$, $R_2 = [43.5, 78]$, and $R_3 = [78, 100]$, which their $P_{up}$ s are 483, 821, and 560 W, respectively. $P_{up}$ of the largest, and using (15), the next sample is taken at $V = 60.7$ V in which (60.75 V, 7.57 A, 460 W). Now, there are four subre-
gions \( R_1 = [9.43.5] \), \( R_2 = [43.5.60.7] \), \( R_3 = [60.7.78] \), and \( R_4 = [78.100] \), which their \( P_{\text{op}} \) s are 483, 655, 581, and 560 W, respectively. \( P_{\text{up-2}} \) is the largest, and using (15), the next sample is taken at \( V = 52.2 \text{ V} \) in which \( (52.2 \text{ V}, 10.67 \text{ A}, 561 \text{ W}) \). Therefore, \( P_{\text{max-3}} \) is updated to 561 W. Since \( P_{\text{op-1}} \) and \( P_{\text{op-2}} \) are lower than \( P_{\text{max-3}} \), GMPP will not be in these subregions. Therefore, candid subregions are limited to \( R_1 = [43.5.52.3] \), \( R_2 = [52.2.60.7] \), and \( R_3 = [60.7.78] \), which their \( P_{\text{op}} \) s are 577, 640, and 581 W. \( P_{\text{up-2}} \) is the largest, but according to (15), \( |V_{\text{mpp}} - V_{\text{r-mpp}}| < 0.5 \text{ V}_{\text{oc-mod}} \). Therefore, no sample is taken in this subregion, and \( R_3 \) which is the next subregion with the biggest \( P_{\text{op}} \) is considered, and using (15), the new sample is taken at \( V = 74 \text{ V} \) in which \( (74 \text{ V}, 6.08 \text{ A}, 450 \text{ W}) \). \( P_{\text{op}} \) in the new subregions \([60.7.74] \) and \([74.78] \) are 551 and 474 W, respectively which both of them are lower than \( P_{\text{max}} \). Therefore, the remaining candid subregions are \([43.5.52.2] \) and \([52.2.60.7] \). The power of the array at \( 43.5 < V < P_{\text{max-1}}/11.08 \approx 50.5 \text{ V} \) is confidently lower than \( P_{\text{max-1}} \), and therefore, the GMPP only can be at the region \([ V_{L}, V_{U}] = [50.5, 60.7] \). Length of this region is about \( 10 \text{ V} \) which is lower than \( 2 \times 0.5 \text{ V}_{\text{oc-mod}} \approx 11 \text{ V} \). Hence, P&O algorithm is called to track the MPP, starting from \( V_{\text{r-pp}} = 52.2 \text{ V} \). The P&O algorithm tracks the MPP at \( (V_{\text{mpp}}, I_{\text{mpp}}, P_{\text{mpp}}) \approx (53.3 \text{ V}, 10.6 \text{ A}, 565 \text{ W}) \). Because \( V_{\text{mpp}} + V_{\text{r-pp}} - V_{\text{mpp-mod}} < V_{L} \), GMPP is terminated, and \( (V_{\text{mpp}}, I_{\text{mpp}}, P_{\text{mpp}}) \approx (53.3 \text{ V}, 10.6 \text{ A}, 565 \text{ W}) \) is the GMPP of the array at PSC1. Next, the P&O algorithm tracks the small changes on the GMPP. It can be seen from the presented procedure that the vicinity of GMPP in PSC1 is achieved just by five samples.

When the PS pattern is changed to the PSC2 at \( t = 1.47 \text{ s} \), the operating point of the array changes to \([53.3 \text{ V}, 6.08 \text{ A}, 324 \text{ W}] \). Similarly, the proposed GMPPPT method tracks the vicinity of the GMPP only with four new samples, and the P&O algorithm gets its exact position at \((V_{\text{mpp}}, I_{\text{mpp}}, P_{\text{mpp}}) = (85 \text{ V}, 5.93 \text{ A}, 504 \text{ W}) \). Finally, the array goes to the UIC2 and its operating point drops from \((85 \text{ V}, 5.93 \text{ A}, 504 \text{ W}) \) to \((85 \text{ V}, 5.31 \text{ A}, 453 \text{ W}) \) at \( t = 2.2 \text{ s} \). Again, the proposed method is activated and it tracks the vicinity of GMPP only with two new samples at \( 9 \text{ V}, 6.11 \text{ A}, 55 \text{ W} \) and \([74.5 \text{ V}, 5.94 \text{ A}, 442 \text{ W}] \), respectively, and then P&O algorithm tracks the exact location of GMPP at \((V_{\text{mpp}}, I_{\text{mpp}}, P_{\text{mpp}}) = (82 \text{ V}, 5.6 \text{ A}, 465 \text{ W}) \). Fig. 8(a) shows the power and voltage of the array during transitions between different irradiance patterns and the operation of the proposed algorithm.

In the following, the operation of the methods presented in [18, 20, 22], and [23] are also simulated in the same test conditions. Description about the operation of these methods is presented in Introduction and details can be found in related papers. Although the presented method in [20] assumes knowing of \( I_{\text{mpp}} \) of the array at the standard test condition, for a fair comparison between the mentioned methods this assumption is not used. Furthermore, [18] assumes that when it is traversed from the either side of the \( P-V \) curve, the magnitude of the peaks increases continuously until the GMPP and decreases continuously after that, and limits the search region using this assumption.

The results including power and voltage of the array during MPPTs are presented in Fig. 8 (a)–(e). When the irradiance pattern changes to PSC1, the presented method in [18] is activated and it tracks the first MPP at \((87 \text{ V}, 520 \text{ W}) \) and the second one at \((65 \text{ V}, 467 \text{ W}) \). Because the second MPP power is lower than the first one, based on the utilized assumption in [18], the method terminates GMPP tracking after 12 samples, and presents \((87 \text{ V}, 520 \text{ W}) \) as GMPP while the actual GMPP is \((53.3 \text{ V}, 565 \text{ W}) \).
Fig. 10. (a), (e) $P-V$ and $I-V$ characteristics of tested array under two PSCs, MPPT process for the first PSC on the array: (b) using the proposed method in this paper, (c) using the presented method in [20], and (d) using the presented method in [18]; MPPT process for the second PSC on the array: (f) using the proposed method in this paper, (g) using the presented method in [20], and (h) using the presented method in [18].

algorithms search process) for three PSCs is considered as total energy loss; the sum of voltage tracks (the sum of absolute values of all voltage steps taken by algorithms from the beginning of PSC to the moment the MPP is found) for three PSCs is considered as total voltage track, and the performance dependency to uniformity of modules for five simulated GMPPT algorithms are presented in Table III. The presented comparisons confirm the overall superiority of the proposed method over the other ones.

VII. EXPERIMENTAL RESULTS

The experimental test results on a sample PV array are presented in this section in order to verify the performance of proposed algorithm practically. The same structure shown in Fig. 1 has been chosen in the experimental tests. Although, the main superiority of the proposed method is on the large size PV arrays, the array used for the experimental test is a $1 \times 5$ array shown in Fig. 9(b). The module type is same as the presented one in Table II. The employed boost converter has the nominal power of 200 W and also $L = 0.6 \, \text{mH}$, $C_{\text{in}} = 34 \, \text{uF}$, and the switching frequency is 40 kHz. The control unit of the system employs the ARM Cortex-M4 32-bit processor.

The performance of the proposed method is tested on two PS patterns, and is compared with the proposed methods in [20] and [18]. In the first PSC, the irradiance level of first four modules is equal to $I_L \approx 0.85 \, \text{kW/m}^2$, and the last one is $I_L = 0.22 \, \text{kW/m}^2$. The corresponding $P-V$ characteristic of the array is shown in Fig. 10 (a). There are two peaks in the $P-V$ curve. It is noteworthy that to extract the $I-V$ and $P-V$ curves, the voltage of the array has been increased with a constant ramp from 0 to $V_{oc-arr}$, and then, the current and power are measured.

Behavior of MPPT tracker using the proposed method in this paper and the methods presented in [18] and [20] are shown in Fig. 10 (b)–(d), respectively. The presented methods in [18] and [20] track the GMPP after 15 and 6 samples, while the proposed method needs only three samples.

In the second PS pattern, the irradiance level of first two modules is equal to $I_L = 0.85 \, \text{kW/m}^2$, and for the three rest modules is $I_L = 0.22 \, \text{kW/m}^2$. The corresponding $P-V$ characteristic of the array is shown in Fig. 10 (e). In this situation, the $P-V$ curve of the array has two peaks. Behavior of MPPT using the proposed method in this paper and the presented methods in [18] and [20] are shown in Fig. 10 (f)–(h), respectively. The presented methods in [18] and [20] tracks the GMPP after 14 and 7 samples, while the proposed approach needs only 4 samples.

Finally, it is worthy note that the proposed method considers the voltage region (2) for searching of GMPP, and it analytically limits the search region. Therefore, it guarantees the tracking of GMPP under any partially shaded conditions. Furthermore, the proposed MPPT method does not need any electrical characteristics of the PV array except of $V_{oc-arr}$ value, which is used to define the search region in (2), and its maximum probable value can be used. Accordingly, the proposed method is not sensitive to the nonuniformity of the modules.

VIII. CONCLUSION

In this paper, a new GMPPT algorithm was presented with a smaller search area for finding the global peak under partially shaded conditions. The proposed method takes some samples and divides the voltage region into some small subregions. Then, $I-V$ curve of the array in each region is approximated...
with a new curve, where its current value is greater than the real one for the same operating voltage. Then, based on the samples and the approximated I–V curves, the search regions for GMPP are limited. Finally, exact GMPP is tracked using P&O algorithm. Through the simulation and experimental results, it was shown that the proposed method tracks the GMPP at all PS patterns with only a few samples and perturbations. The results of this work were compared with the results of the four other methods, and its better performance was confirmed in all test conditions. The proposed MPPT method is not sensitive to the module parameters and even can track the MPP of an array with different type of PV modules.

**References**


