AN EFFICIENT MPPT ALGORITHM FOR PARTIALLY SHADED PV STRINGS

Efstratios BATZELIS(1) Stavros PAPATHANASSIOU(1)

(1) NTUA, Electric Power Division, 9 Iroon Politechniou str., 15780, Athens, Greece

e-mail: batzelis@mail.ntua.gr, st@power.ece.ntua.gr

ABSTRACT: Under partial shading conditions, several power peaks (maximum power points - MPPs) are presented on the *P-V* curve of a photovoltaic system, hindering the effectiveness of typical maximum power point tracking (MPPT) algorithms, due to possible convergence to a local suboptimal MPP. In this paper, a global MPPT (GMPPT) method for PV strings is proposed, which exploits the theoretical MPP characterization to detect the shading conditions and estimate all MPPs on the *P-V* curve. The calculations performed do not involve unnecessary operating point variations and output power fluctuations. The proposed method is designed for PV strings illuminated at two irradiance levels and only needs the standard voltage and current sensors of the DC/DC converter.

Keywords: Maximum power points (MPPs), Maximum power point tracking (MPPT) algorithm, Partial shading, photovoltaic (PV), Power peaks.

1 INTRODUCTION

Typical maximum power point tracking (MPPT) algorithms, such as perturb & observe (P&O) and incremental conductance (INC), usually do not face difficulties in locating the single power peak presented on the *P-V* characteristic curve of a uniformly illuminated photovoltaic (PV) system. However, under uneven irradiance distribution (often designated by the term *partial shading conditions*), several power peaks (or maximum power points – MPPs) appear on the *P-V* characteristic of the PV generator. In such conditions, the standard MPPT algorithms often fail to locate the global MPP and converge to one local MPP, leading to suboptimal operation and reduced MPPT efficiency.

Several papers are found in the literature that study this particular subject and develop strategies capable of surpassing, or at least mitigating, this effect. In general, there are four main options to address this issue [1]: enhancing the MPPT algorithm so that it always locates the global maximum regardless of the irradiance distribution, by changing the PV array configuration (interconnection schemes between PV modules) or resorting to more complicated system architectures (microinverters etc.), and enhancing the converter capabilities with the inclusion of extra circuits. A comprehensive literature review on these subjects is given in [1].

The focus of this paper is on the first option, namely the improvement of classic MPPT algorithms in order to always operate optimally, under both uniform illumination and partial shading conditions (global MPPT – GMPPT). In [2], such an algorithm is proposed that periodically performs curve fits on certain parts of the *P-V* characteristic, based, however, on specific empirical observations. Other methods that perform sophisticated operating point variations are given in [3] and [4], albeit still inducing a not insignificant fluctuation on the output power. Other approaches adopt evolutionary optimization algorithms to minimize the search duration of the global maximum and therefore the operating point perturbation, such as [5] and [6], which employ particle swarm optimization (PSO).

However, the main drawback of all aforementioned methods is the necessity to periodically perturb the operating point. This inevitably entails undesired fluctuation on the output power, as well as, short-term power losses during the operating point variation. In order to balance the pros and cons, the execution frequency of the GMPPT is properly adjusted in these papers, still compromising between losses due to partial shading and the aforementioned implications.

In this paper, a GMPPT method is introduced that mathematically estimates all local MPPs on the *P-V* curve, *without* perturbation of the actual operating point. The proposed method is based on the theoretical analysis and characterization presented in [7], utilizing specific equations to detect the shading conditions by only using the measured values of the actual operating voltage and current. The same equations provide then the power and voltage of all MPPs and thus the global maximum location on the *P-V* curve, regardless of the actual operating region. This way, the developed algorithm continuously monitors the global MPP and properly shifts the operating point when needed, while the calculations performed are entirely mathematical, avoiding unnecessary operating point variation and output power fluctuation. This permits continuous execution of the proposed GMPPT algorithm (e.g. 10 times per second or more), compared to other approaches that need to perturb the operating point and are therefore bound to much lower execution frequencies (e.g. once every few minutes), thus providing optimal adaptation to rapidly changing partial shading conditions. The method is designed for PV strings illuminated at two irradiance levels. It does not require an irradiance sensor or other additional components, except for the standard voltage and current sensors of the DC/DC converter. The effectiveness of the proposed GMPPT method is validated and compared to the typical P&O approach through simulations in MATLAB/Simulink.

The structure of the paper is as follows: a theoretical analysis of the local MPP trends is given in Section 2, providing the basis for the developed algorithm presented in the Section 3. Its effectiveness is validated through simulations in Section 4, while the main conclusions are summarized in the final section.

2 MPP CHARACTERIZATION

In order to study the partial shading phenomenon on PV strings, a notation similar to the one used in [7] and [8] is adopted. A PV string consists of several PV modules connected in series, while a PV module comprises series connected PV cells. A group of series connected cells within a module, with a bypass diode connected in parallel to its terminals, is denoted as a *cell string*. Under partial

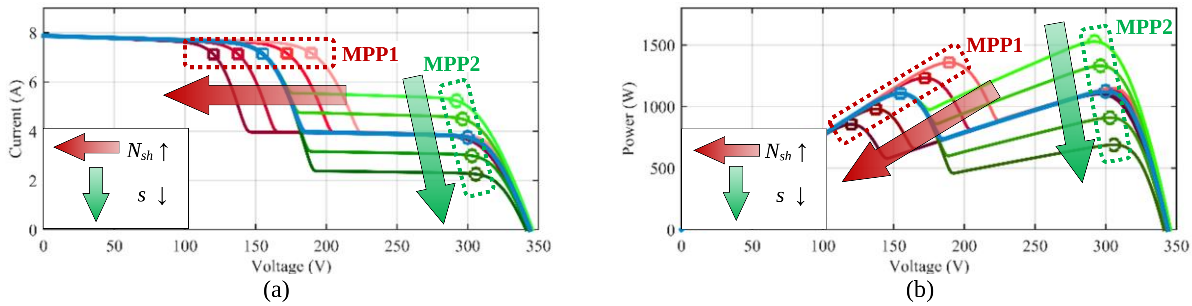

Figure 1: (a) *I-V* and (b) *P-V* curves of a PV string illuminated at two irradiance levels. The red square markers correspond to MPP1 and the green circle markers to MPP2; the red and green arrows show how the characteristics are modified when the shade extent (N_{sh}) or shade ratio (s) change.

shading conditions, assuming two irradiance levels (i.e. one level of shade), each cell string is either shaded or unshaded, being illuminated at an irradiance G_{sh} or G_{un} ($G_{un}>G_{sh}$) respectively. The shading ratio is defined as $s=G_{sh}/G_{un}$. The shaded and unshaded parts of the string comprise N_{sh} and N_{un} cell strings ($N_{tot}=N_{sh}+N_{un}$) respectively. As shown in [7]–[9], up to two MPPs may appear on the *P-V* curve of the string, denoted MPP1 and MPP2. When operating at MPP1, the shaded cell strings are bypassed and only the unshaded cell strings generate power; at MPP2, all cell strings contribute to power generation at the reduced current dictated by the shaded cell strings.

To facilitate understanding, the *I-V* and *P-V* curves of a partially shaded PV string, illuminated at two irradiance levels, are illustrated in Figure 1, for different extents and intensities of shadow. The red square markers correspond to MPP1, whose voltage V_{mp1} varies almost linearly with the shade extent N_{sh} (red arrow), whereas its current I_{mp1} remains constant (Figure 1(a)). On the other hand, the voltage V_{mp2} of MPP2 (green circle markers) is only slightly affected by the shade intensity (green arrow), while its current I_{mp2} varies linearly with the shade ratio s.

It is worth noting that MPP1 is affected only by the extent of the shadow N_{sh}, and not by the shading intensity, since the shaded part of the PV string is bypassed (Figure 1). On the contrary, MPP2 mainly depends on the shading ratio s, as all cell strings operate at the same current determined by the lower irradiance level, and to a much lesser degree on the extent of the shadow N_{sh} (Figure 1).

3 PROPOSED GMPPT ALGORITHM

As shown in Figure 1(b), the global maximum may be MPP1 or MPP2, depending on the shading parameters N_{sh}, G_{sh} and G_{un}. The intensity of a particular shade pattern does not considerably change during the day, even though the absolute irradiance levels G_{sh} and G_{un} may vary. Hence, during typical shading events, the characteristic curves are predominantly modified following the red arrow in Figure 1(a)-(b), rather than the green one. As shown in Section 4, a standard P&O MPPT algorithm begins operation at the single MPP when the system is unshaded, but converges to MPP1 as the shadow appears and extends, even though it is not the global maximum at all times (Figure 1(b)).

In order for a GMPPT method to be able to recognize whether the actual operating point corresponds to the global maximum or not, both MPPs have to be known in terms of power and voltage values. In this paper, this is achieved adopting the MPP expressions introduced in [7]:

$$\text{MPP1:}\begin{cases} V_{mp1} = N_{un}V_{mp0} - N_{sh}\Delta V_D \\ I_{mp1} = G_{un}I_{mp0} \end{cases} \quad (1)$$

$$\text{MPP2:}\begin{cases} V_{mp2} = N_{un}\left(sV_{mp0} + (1-s)V_{oc0}\right) + N_{sh}V_{mp0} \\ I_{mp2} = G_{sh}I_{mp0}\left(1 + \lambda\dfrac{N_{un}}{N_{tot}}\right) \end{cases} \quad (2)$$

where V_{mp0}, I_{mp0} and V_{oc0} are the nominal MPP voltage, MPP current and open circuit voltage of the cell string, as provided in the module datasheet, while ΔV_D corresponds to the voltage drop on a conducting bypass diode (typically around 1 V) and λ is an empirical coefficient equal to 0.06.

In order to use (1) and (2), the shading parameters N_{sh}, G_{sh} and G_{un} are required, which are not known a priori, nor is there any practical way to be physically measured. However, they may be indirectly estimated, utilizing the voltage and current measurements at the actual MPP.

Specifically, if the actual operating point is MPP1 and the shade ratio s is considered to be known, N_{sh} and G_{un} are calculated reformulating (1), using the measured values V_{mp1} and I_{mp1}, while G_{sh} is determined exploiting the definition of the shade ratio s:

$$N_{sh} = \frac{N_{tot}V_{mp0} - V_{mp1}}{V_{mp0} - \Delta V_D} \;\Downarrow\; G_{un} = \frac{I_{mp1}}{I_{mp0}} \;\Downarrow\; G_{sh} = sG_{un} \quad (3)$$

Using expressions (3), the shading conditions are determined and then the MPP2 voltage and current, V_{mp2} and I_{mp2}, are estimated from (2). Similarly, if operating at MPP2, (2) is solved for N_{sh} and G_{sh}:

$$N_{sh} = \frac{N_{tot}(sV_{mp0} + (1-s)V_{oc0}) - V_{mp2}}{(1-s)(V_{oc0} - V_{mp0})} \;\Downarrow\; G_{sh} = \frac{I_{mp2}}{(1+\lambda N_{un}/N_{tot})I_{mp0}} \;\Downarrow\; G_{un} = s/G_{sh} \quad (4)$$

and then V_{mp1} and I_{mp1} are evaluated using (1).

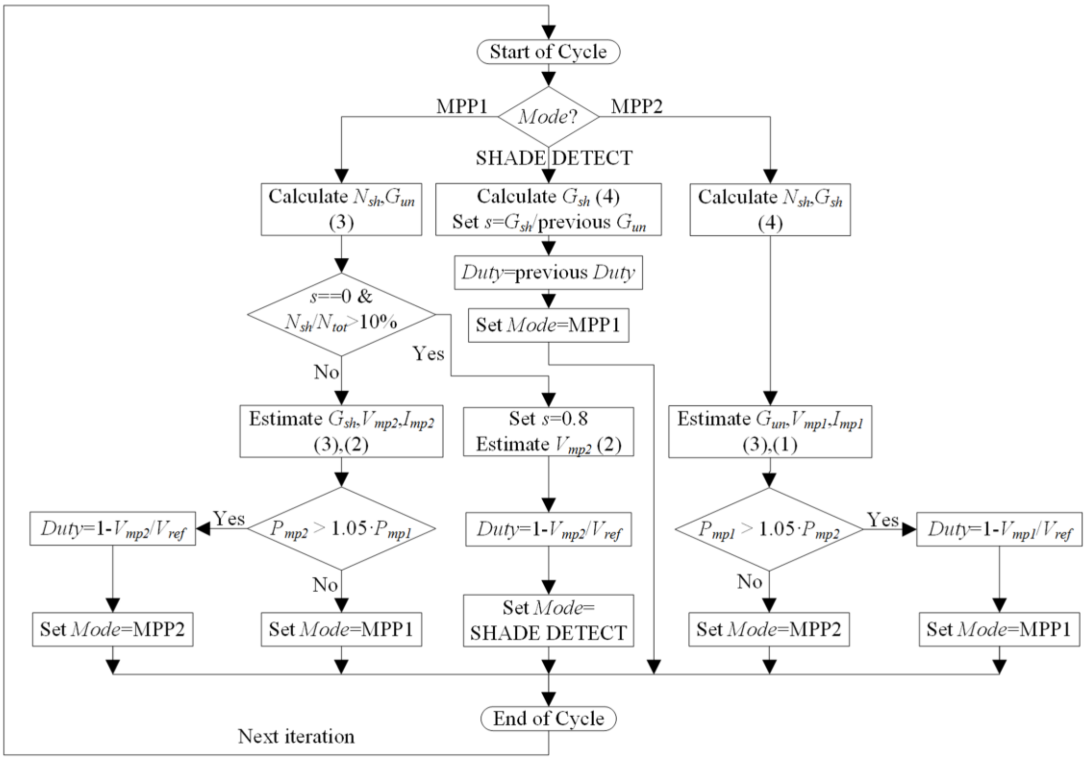

Figure 2: Flowchart of the proposed GMPPT method. The algorithm detects the actual shading conditions given the current MPP and estimates the other MPP's properties, performing a transition only if the latter provides a higher power (duty cycle set for boost converter). At the beginning of shading, the shade ratio is measured with an instant transition.

The above calculations require the shade ratio *s*, which is not generally known beforehand. However, if the intensity of shadow is assumed to be near-constant for a particular shading incident, as discussed above, then *s* can be determined once, at the emergence of shading, and then this value can be utilized thereafter. As described in the following, the proposed algorithm performs a shade detection procedure only once, by shortly varying the array operating point, without repeatedly perturbing the operation of the system and its output power.

In Figure 2, the flowchart of the proposed method is illustrated. The GMPPT algorithm is executed in addition to the classic P&O technique, albeit at a lower frequency (typically once every 10-20 cycles of P&O). Each time the GMPPT is executed, the proper branch of the algorithmic diagram is selected, depending on the actual mode: currently operating at MPP1 (left branch), currently operating at MPP2 (right branch), or in shade detection operation (middle branch). Initially, the mode is set to MPP1, since the system is unshaded and the single MPP presented corresponds to MPP1.

If the mode is MPP1 or MPP2 (left or right branches), the shading parameters N_{sh} and G_{un}/G_{sh} (G_{un} in the left branch, G_{sh} in the right branch) are first determined. Then, if in MPP1 mode, the next steps depend on whether the shade ratio *s* is known. If *s* has been already calculated, the remaining unknown irradiance G_{sh}/G_{un} is determined and the properties of the other MPP are then estimated (G_{sh}, V_{mp2}, I_{mp2} in the left branch – G_{un}, V_{mp1}, I_{mp1} in the right branch). Thereafter, the estimated power at the other MPP is compared to the actual power at the current MPP: if the deviation is more than a tolerance limit (e.g. 5%), then a transition to the other MPP is performed. In Figure 2, the duty cycle is calculated for a boost DC/DC converter, utilizing the estimated voltage of the other MPP and the reference dc link voltage V_{ref}. In either case, the mode is updated to MPP1 or MPP2, depending on the result of the power comparison, and then the current execution cycle of the GMPPT algorithm is finalized. Thereafter, the classic P&O algorithm, which is continuously active, fine tunes the operating point to correct any possible estimation error and thus converge to the new MPP. The GMPPT is executed again after a certain number of P&O cycles have elapsed.

Initially, when there is no shading, the algorithm starts at MPP1 and the shade ratio is *s*=0, since shading is still unknown. The latter is measured for the first time when partial shading appears at an extent of more than 10%. This procedure begins by arbitrarily setting *s*=0.8, in order to obtain an approximation of V_{mp2}, followed by a transition to the latter and a mode update to SHADE DETECT. In the subsequent step of the algorithm, the upper half of the middle branch is executed: G_{sh} is determined using the measured current at the new operating point, and then this is used to estimate *s* in conjunction with the previously calculated G_{un}. This mode lasts for just one GMPPT period, which suffices for the shade ratio determination, and then the previous duty cycle that corresponds to MPP1 is restored. This way, the entire shade detection procedure does not practically affect the output power.

It is worth noting that the arbitrary high value of *s* (*s*=0.8) is selected to underestimate, rather than overestimate, V_{mp2}, since this leads to an operating current very close to the actual I_{mp2}, due to the small slope of the *I-V* curve left of MPP2 [7] (Figure 1(a)).

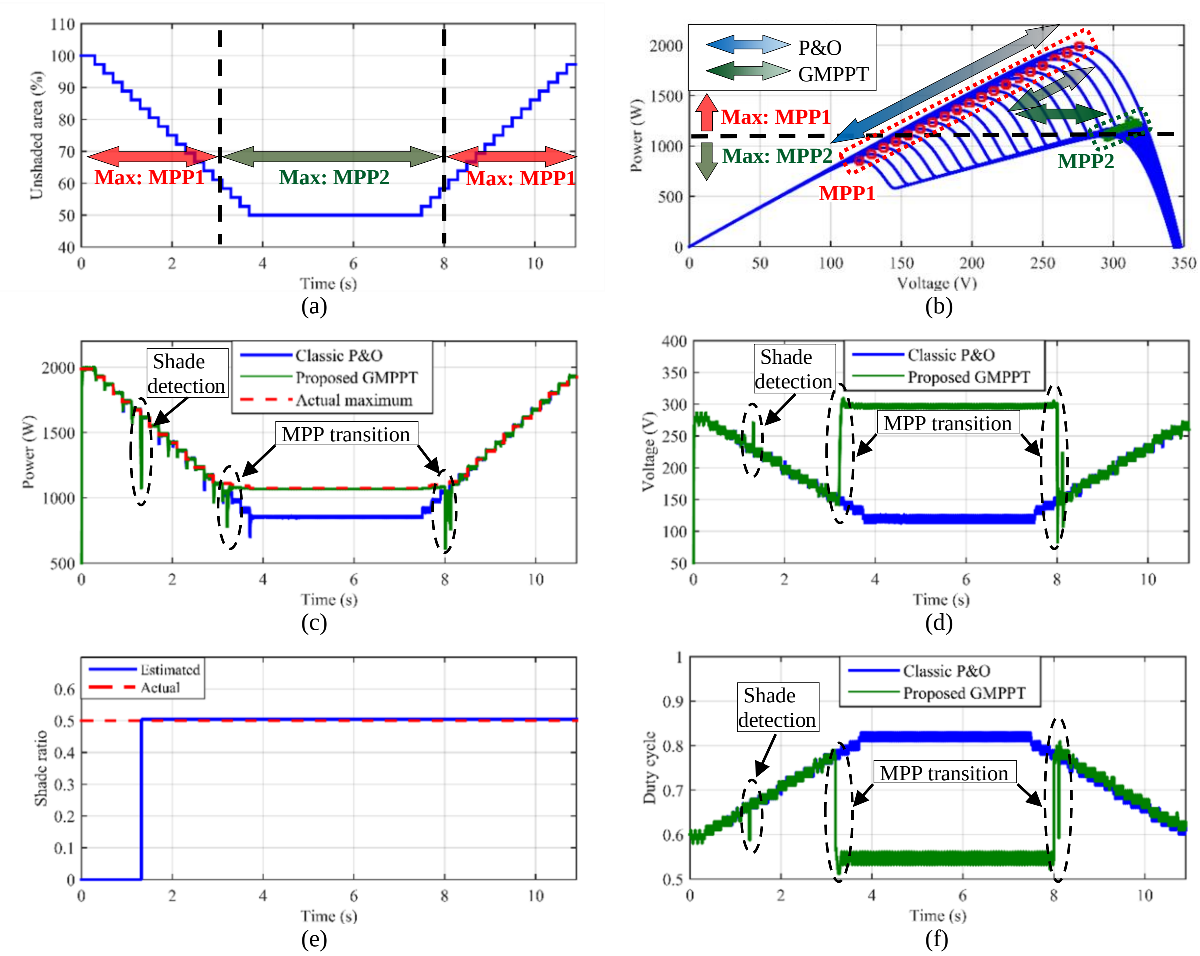

Figure 3: Simulation of a PV string partially shaded at 50% intensity and time varying extent, applying a typical P&O algorithm and the proposed GMPPT method. (a) Unshaded string area, (b) *P-V* curve variation, (c) power output, (d) operating voltage, (e) shade ratio and (f) DC/DC converter duty cycle.

4 SIMULATIONS

To illustrate the effectiveness of the proposed GMPPT method and its superiority over the classic P&O algorithm, the indicative scenario of Figure 3, is considered. A PV string composed by 12 PV modules, each comprising 3 cell strings, is subjected to a short-term shading of a few seconds, during which its area is gradually shaded up to 50%, while the shade ratio remains constant at 50% (Figure 3 (a)). The form of the *P-V* curve, as it changes over time, is depicted in Figure 3 (b), in which MPP1 and MPP2 are indicated with red square and green circle markers respectively.

MPP1 is the global maximum, except during the interval from t=3 s to t=8 s (Figure 3 (a)), when the extent of the shadow exceeds 40% of the string area, rendering MPP2 the global MPP (Figure 3 (b)). Initially when the system is still unshaded, the classic P&O MPPT algorithm operates at the single MPP presented, which corresponds to MPP1 (highest power red square mark in Figure 3 (b)). As the shadow extends and the *P-V* curve changes over time as Figure 3 (b) shows, the P&O method continuously fine tunes the operating point, constantly relocating MPP1 to its new position in the immediate vicinity. This effectively leads to the operation of the PV string being locked at MPP1 for the entire period, as shown with the blue arrow in Figure 3(b), even when MPP1 is not the global maximum. On the contrary, the proposed GMPPT method switches to MPP2 when the latter becomes the global MPP, thanks to the detection mechanism developed (between 3 s and 8 s, shown by green arrows in Figure 3(b)).

The output power produced with each algorithm is depicted in Figure 3(c), along with the maximum available power under ideal MPP tracking (red dashed line). As expected, the P&O method (blue line) operates suboptimally in the interval 3-8 s, when MPP2 is the global maximum. On the contrary, the GMPPT algorithm (green line) continuously monitors the global MPP and performs the proper transitions at the t=3 s and t=8 s, leading to optimal power generation, almost coinciding with the theoretical maximum.

The transitions performed are clearly visible in Figure 3(d) and Figure 3(f), where the operating voltage and duty cycle vary significantly depending on the actual MPP type. The one-step shade detection procedure takes place at t=1.3 s, causing a very brief fluctuation of the output power (Figure 3(c)) and resulting in a highly accurate estimation of the shade ratio s=0.505 (Figure 3(e)).

5 CONCLUSIONS

In this paper, a new GMPPT technique is introduced, capable of continuously monitoring the global maximum and shifting properly the operating point when needed by the prevailing shading conditions. The calculations involved are very simple and can be easily implemented on a microprocessor, while the monitoring mechanism is based on analytical mathematical expressions, avoiding unnecessary perturbation of the operating point, such as during a curve scanning procedure, thus maintaining a high tracking efficiency and reduced output power fluctuations. Simulation results validate the efficient tracking performance for a PV string operating under partial shading conditions of two irradiance levels.

6 ACKNOWLEDGMENTS

Mr. E. Batzelis is supported in his PhD studies by "IKY Fellowships of Excellence for Postgraduate Studies in Greece - Siemens Program".

7 REFERENCES

[1] A. Bidram, A. Davoudi, and R. S. Balog, “Control and circuit techniques to mitigate partial shading effects in photovoltaic arrays,” *IEEE J. Photovoltaics*, vol. 2, no. 4, pp. 532–546, Oct. 2012.

[2] H. Patel and V. Agarwal, “Maximum power point tracking scheme for PV systems operating under partially shaded conditions,” *IEEE Trans. Ind. Electron.*, vol. 55, no. 4, pp. 1689–1698, Apr. 2008.

[3] Y.-H. Ji, D.-Y. Jung, J.-G. Kim, J.-H. Kim, T.-W. Lee, and C.-Y. Won, “A real maximum power point tracking method for mismatching compensation in PV Array under partially shaded conditions,” *IEEE Trans. Power Electron.*, vol. 26, no. 4, pp. 1001–1009, Apr. 2011.

[4] E. Koutroulis and F. Blaabjerg, “A new technique for tracking the global maximum power point of PV arrays operating under partial-shading conditions,” *IEEE J. Photovoltaics*, vol. 2, no. 2, pp. 184–190, Apr. 2012.

[5] M. Miyatake, M. Veerachary, F. Toriumi, N. Fujii, and H. Ko, “Maximum power point tracking of multiple photovoltaic arrays: A PSO approach,” *IEEE Trans. Aerosp. Electron. Syst.*, vol. 47, no. 1, pp. 367–380, Jan. 2011.

[6] K. Ishaque, Z. Salam, M. Amjad, and S. Mekhilef, “An improved particle swarm optimization (PSO)–based MPPT for PV with reduced steady-state oscillation,” *IEEE Trans. Power Electron.*, vol. 27, no. 8, pp. 3627–3638, Aug. 2012.

[7] E. I. Batzelis, I. A. Routsolias, and S. A. Papathanassiou, “An explicit PV string model based on the Lambert W function and simplified MPP expressions for operation under partial shading,” *IEEE Trans. Sustain. Energy*, vol. 5, no. 1, pp. 301–312, Jan. 2014.

[8] G. N. Psarros, E. I. Batzelis, and S. A. Papathanassiou, “Partial shading analysis of multistring PV arrays and derivation of simplified MPP expressions,” *IEEE Trans. Sustain. Energy*, vol. 6, no. 2, pp. 499–508, Apr. 2015.

[9] E. V. Paraskevadaki and S. A. Papathanassiou, “Evaluation of MPP voltage and power of mc-si PV Modules in partial shading conditions,” *IEEE Trans. Energy Convers.*, vol. 26, no. 3, pp. 923–932, Sep. 2011.