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A critical evaluation of maximum power point tracking techniques for PV systems working under partial shading conditions

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Abstract

Photovoltaic (PV) energy is a promising source of renewable energy which is sturdy and environmentally friendly. PV generation systems, once installed, produce electricity from solar irradiance without emitting greenhouse gases. To maximize the output power of PV systems, the maximum power point tracking system has been employed (MPPT). The MPPT constitutes a fundamental part of PV systems. In recent years, a large number of MPPT techniques have been proposed. This paper is set up to critically review some of the proposed maximum power point tracking (MPPT) techniques to handle the emergence of multiple MPPs in PV panel characteristics due to the partial shading conditions (PSCs). To define the working principle and the pros and cons of the different proposed techniques clearly and sequentially, they are divided into three groups as follows: conventional MPPT techniques, improved MPPT techniques and artificial intelligence- based MPPT techniques to deal with PSCs. The paper also critically summarizes the findings in terms of their performance in capturing the global maximum power point (GMPP) for PV systems operating under PSCs.

1. Introduction

Nowadays, as a result of fossil fuel depletion, the importance of renewable energy has reached an unprecedented height. The photovoltaic (PV) systems are considered one of the most distinctive systems among the resources of renewable energy because they have many merits, for example, availability, low maintenance, environmental friendliness and a longer lifespan [1]. As a result of these advantages, the PV systems are developing rapidly throughout the world, where the PV energy generation shows a significant development compared to other types of renewable energy sources [2].

However, despite all the successive improvements in the PV industry, Solar cells still have some drawbacks such as high manufacturing cost, low efficiency, degradation of the cells and the fact that the initial investment cost of the solar system is high compared to the traditional fossil fuel systems. Moreover, the nonlinear characteristic of the solar cell (shown in Fig.1) depends on several factors such as the irradiance level and ambient temperature and that have limited the global utilization of the PV system [3] . To overcome these drawbacks and increase the efficiency of the PV system, Maximum Power Point Tracking (MPPT) has been considered as the main solution [4]. The MPP is the point on the current-voltage (I-V) curve that indicates the maximum power that a solar panel can produce under certain climatic conditions as shown in Fig. 1 [5] [6]. Maximum power point tracker (MPPT): an electronic device which continuously searches for the MPP of a PV panel and then makes the operating point of the system at the MPP. In another word, the main purpose of MPPT is to oblige the PV system to operate at a point where maximum efficiency level is obtained. Yet, the strong dependence of the PV system upon the atmospheric conditions makes extracting the maximum available power from its nonlinear characteristics more difficult. To handle these issues, many of MPPT techniques have been proposed to make the PV power generation system operate at the optimal point. The proposed techniques

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vary in several aspects such as convergence speed, complexity, cost, implementation hardware, sensors required and range of effectiveness [7]. These techniques can be divided into conventional MPPT techniques, improved MPPT techniques and artificial intelligence-based MPPT techniques to handle the PSCs. In the following sections, we will provide a reference study on the most important proposed techniques, along with an account of their pros and cons.

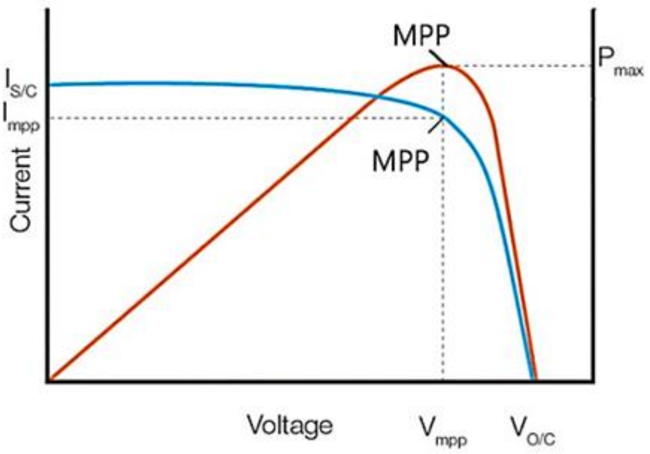

Figure 1. I-V and P-V curve of a PV panel

Where:
V_{MPP}: the voltage at the maximum power point.
I_{MPP}: the current at the maximum power point.
I_{SC}: the short circuit current.
V_{OC}: the open-circuit voltage.

2. Conventional MPPT Techniques

Several conventional MPPT techniques have been proposed and there has been considerable research on them [8] [9]. Among the conventional techniques mentioned in these publications are perturbation and observation (P&O) [10], [11], hill climbing (HC) algorithm [12], fractional open circuit voltage and short circuit current methods [13], switching ripple correlation [14], sliding mode control [15], incremental conductance (IC) [16] [17], constant voltage [18] and some other techniques [19]. Amongst the conventional MPPT techniques, the P&O and HC algorithms are considered the most popular ones due to their ease of implementation [20]. The working principle of both algorithms depends on changing the control parameter by a constant value and exploring whether the MPP has been captured or not. The direction of changing the control parameter is determined based on the increase in the power produced. Besides, the IC algorithm is considered one of the most used conventional algorithms due to its high performance. It is based on computing the differential of the PV power to PV voltage to determine the location of the operating point, where the differential is zero at the MPP [21].

Although these techniques can catch the optimal point of the PV panels under uniform solar irradiance conditions, they fail to capture the GMPP of the PV panels operating under PSCs. Under PSCs, the PV panel characteristics exhibit many local maximum power points (LMPPs) and one global MPP (see Fig.2) due to the use of the bypass diodes to handle the hot spot phenomena [22]. In this situation, to accurately capture the GMPP, and avoid trapping in one of the LMPPs, optimized techniques are required.

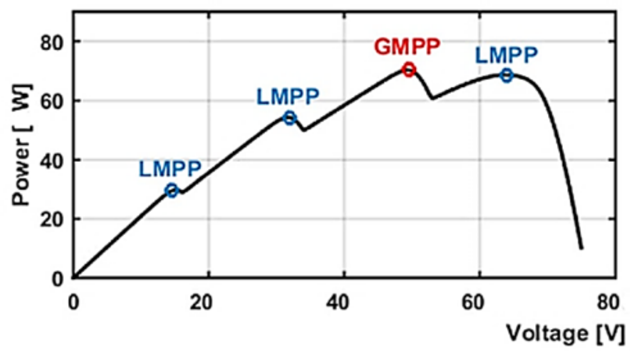

Figure 2. Partially shaded PV panel curve

3. Improved MPPT Techniques to Deal with PSCs

To overcome the drawbacks of the conventional MPPT techniques and handle the PSCs issue, researchers have developed new MPPT techniques, some of which are addressed here. The method introduced in Ref. [23] is an improved IC algorithm. This method is able to capture the GMPP by distinguishing all MPPs in the P-V characteristic. However, a wide range of data, which are the electrical parameters of the PV panels, is required. In Ref. [24], to achieve the GMPPT, an extremum seeking control is proposed. Notwithstanding that this technique has a rapid dynamic response, it requires more information about the electrical parameters of the PV panels. The technique proposed in [25] improved the transient response of the PV system and increased the tracking speed by scanning the entail P-V characteristic of the PV array. However, implementation of this technique requires a high-performance processor, which makes the overall PV system cost- inefficient. The proposed algorithm in [26] is based on the open-circuit voltage of the PV array to estimate the possible GMPP, then the P&O algorithm is employed to track the GMPP. Although this algorithm has a good dynamic tracking performance, it could fail in finding the GMPP under complex PSCs. In Ref. [27] & [28], to decrease the tracking time, a beforehand calculating of the regions of all MPPs is proposed, which, however, requires a great deal of data related to the structure of the PV array which is difficult to obtain or predict. In Ref. [29], a distributed MPPT (DMPPT) algorithm is proposed in order to compensate for the energy loss due to PSCs. This technique requires an increase in the number of converters used; however, this will increase the cost of the whole system. To achieve GMPPT, a two-stage method is outlined in Ref. [30], while Ref. [31] describes a Fibonacci sequence-based technique. However, they were not able to find GMPP in all cases. In Ref. [32], additional sensors are required to implement the algorithm proposed which increase the implementation cost. In Ref. [33], to detect the PSC, a method based on calculating the solar irradiance at two different points is proposed. The aim of using this technique is to avoid unnecessary searching for GMPP. The research in Ref.

[34] introduced innovation technique with the comparison of power tracked in incremented duty cycle during GMPPT process. Although effective results were obtained in this research, the scan and sampling processes throughout the P-V characteristic are still required. In Ref. [35], the authors demonstrated that if the P-V curve has multiple MPPs, the algorithm may be unable to identify the true MPP. In Ref. [36] & [28], to improve the performance of the conventional MPPTs, the authors proposed using the "skipping" mechanism. In this approach, specified voltage intervals will not be scanned because the algorithm has already detected that GMPP is not located in those divisions. In this approach, the tracking speed is improved as a result of reducing the search space. Both maximum power trapezium algorithm (MPT) [36], and voltage window search algorithm (VWS) [28], are based on skipping mechanism. In MPT algorithm, during convergence to the GMPP, the sample of current and voltage are used to update the following voltage references. Although convergence speed is improved, the MPT algorithm possibly does not find GMPP if the chosen voltage step is incorrect.

In Ref. [37], the search-skip-judge approach (SSJ) is proposed. In this method, the section dividing points (SDP) are determined using the short-circuit current values of the shaded modules, which in turn determine the unnecessary voltage periods, so that they can be overshooted. However, according to Ref. [35], if the GMPP is located far at the other end of the P-V curve, the convergence speed of the SSJ will be low. In Ref. [38], to detect the shading, light-detecting resistors (LDRs) were positioned on each PV module. Once the LDRs are shaded, the method becomes active for defining shaded modules; otherwise, the method is ineffective. In Ref. [39], for better detecting shaded modules, authors proposed using PV modules' respective analog sensors to collect their electrical properties. However, the limitations of analog sensing design with respect to the PV modules were not properly discussed. Furthermore, such data can be collected without using analog sensors.

Considering the high cost of analog sensors, authors in Ref. [40] & [41] proposed a technique based on the measured voltage (VPV) and measured current (IPV). The technique starts scanning the P-V curve and its operation initiates from the far-right region, and the scanning process stops if the theoretical power of the next section is less than the practical power of the current section. However, this method suffers if two peaks are quite away from each other. In another technique proposed in ref [42], the power slope of each section is examined to determine the GMPP. Even though this technique presented good performance, it cannot distinguish between regular and PSCs. Arrow Sudoku puzzle pattern which is one of the reconfiguration techniques is studied for PV system under PSCs in ref [43]. To implement such techniques, programmable power switches are required. However, solid-state power switches are expensive while mechanical power switches are slow and may degrade over time. In ref [44], the authors proposed a technique to estimate the location of GMPP by using the voltage in various sub-assemblies of PV modules through determining the irradiance levels in the sub-assemblies. Although the technique introduced good performance under PSCs, implementing this technique requires additional sensors which makes the system more complex and expensive. In Ref. [45] authors introduced a GMPP tracking method by dividing the voltage range of the PV array, and then samples are taken in each section to narrow down the search space and determine the optimal section in which GMPP occurs. However, this technique does not guarantee to find the GMPP under all partial shading patterns; furthermore, many samples are needed at different points to compare with predefined constants to determine any change in irradiance pattern.

4. Artificial Intelligence-Based MPPT Techniques to Deal with PSCs

To date, many artificial intelligence- based MPPT techniques have been proposed to address the PSCs issue. In this subsection, several pieces of research are summarized to provide a comparative study of the most frequently adopted AI-based MPPT techniques.

To achieve global MPPT, in Ref. [46] & [47] particle swarm optimization (PSO) and in Ref. [48] the genetic algorithm (GA) were proposed. Although PSO is simple in implementation and able to find the optimal point, it is computationally intensive and time-consuming which gradually reduces search accuracy. As well GA is complex and requires a long computation time to capture the GMPP. In Ref. [49], a modified PSO method is proposed. In this algorithm, due to the use of many variables with a random number, more iterations are required to find GMPP perfectly, and this makes the convergence speed to GMPP lower than PSO. In the last years, the ant colony algorithm and simulated annealing algorithm have also been proposed to achieve the GMPPT [50]. Modified Java MPPT algorithms were proposed in Ref. [51] & [52], and this algorithm does not require specific parameters. According to the experimental results in Ref. [53] & [50], for increasing the tracking speed of the AI-based MPPT algorithms, suitable initial parameters are required. By assigning the initial values of AI-based MPPT algorithms, the region containing the GMPP can be determined and thus, the tracking speed can be improved [54], [55], [56]. Numerous strategies in identifying the region of the GMPP are documented in Ref. [54], [55] and [56]; however, they required a great deal of information about PV panels characteristics, and this may increase the complexity of implementing these algorithms, given the need to test devices before implementation. In Ref. [57], a fuzzy logic (FL)- based algorithm is proposed. In this algorithm, the slope of the P-V characteristic is the input while the value of the duty cycle is the output. Seven membership functions are used for both the input and the output, and the system has a set of seven rules. In this technique, the whole P-V curve is scanned and the value of the duty cycle which is corresponding to GMPP is stored. In Ref. [58], another FL based MPPT with 7 membership functions and 49 rules is proposed. In this research, error in power and change in error are considered. These FL based MPPT techniques introduced high performance rather than conventional techniques; however, they require more time to converge to the optimal MPP due to large search space.

In addition, MPPT methods are implemented depending on many metaheuristic techniques including cuckoo search [59], grey wolf optimization (GWO) [60], and bat algorithm (BA) [61]. To acquire the benefits of two techniques together, hybrid optimizations were proposed in some papers [60], [62]. In these proposals, two different techniques are used together under different operating conditions. Using these techniques in MPPT applications was evaluated in Ref. [63]. However, the inherent problem in metaheuristic techniques is that they cannot determine the optimal initial value of the duty cycle. As a consequence, they are unable to improve the convergence speed and dynamic variation of the shading patterns. In Ref. [64] BA was proposed as an MPPT of PV systems supplying synchronous reluctance motors. The author tested both BA and PSO techniques under the same conditions and the collected results were compared. BA presented better performance than PSO; however, the problems related to the PSCs, or the dynamic variation of shading patterns were not discussed. In Ref. [65] & [66], firefly algorithm (FA), which is one of the nature-inspired techniques is proposed. It has the advantages of simple computational processes with low power disturbance. Notwithstanding, under PSCs, it may not find the GMPP, and be trapped in one of the LMPPs due to the inherent over-attraction issue [67]. In Ref. [68], to increase the MPPT speed, a modified firefly MPPT algorithm was proposed. The author proposed simplifying the movement rules of fireflies to increase the convergence speed to GMPP. Even though this problem was mitigated by the modified FA, the convergence speed is still slow [69]. Although simplified FA (SFA), which was proposed in Ref. [65], has better convergence speed, it has lower accuracy in capturing GMPP. To deal with this a hybrid approach was proposed in Ref. [70]. The modified FA is used to identify the GMPP, then the P&O algorithm is employed to track it. The results demonstrated that the proposed approach exhibits high performance in tracking the GMPP and improves the convergence speed. In Ref. [71], artificial neural network (ANN) is used to track GMPP under PSCs. However, this technique needs prior training on the PV modules being used. In Ref. [72], General Regression Neural Network (GRNN) was proposed to find the GMPP under PSCs. This technique showed good performance in capturing GMPP; however, implementing such a technique requires a sophisticated embedded system; moreover, the convergence speed to GMPP is slow. In Ref. [73], to achieve GMPPT, a hybrid technique was proposed, which is based on a scanning technique combined with a fuzzy logic technique. In this technique, the entail P-V curve is scanned to capture the GMPP. However, the method on which the scanning depends was not clear. Furthermore, since the observation stating the increasing and decreasing trends when moving far from GMPP cannot be true under all conditions, it was disagreed by [74]. In the technique proposed in Ref. [74], the process of scanning the P-V curve and determining the GMPP was achieved by using a switch in the boost converter for executing the short-circuiting. Regardless of the approach seems excellent, a DSP processor and high-speed ADC are required for sampling the entire data, which increases the implementation cost. Additionally, if the scanning is performed repeatedly under a frequent change in irradiance, then discharging of energy stored in the input capacitor will reduce the efficiency of the system.

A combination between P&O algorithm and the genetic algorithm was proposed in Ref. [54] & [75]. In this combination, the performance of the P&O algorithm was improved in PSCs. Practically, the genetic algorithm identifies the location of GMPP; thereafter, the P&O algorithm tracks the GMPP of the system. Although the performance of the P&O algorithm is improved, it requires much time to track GMPP. Both memory self-organizing incremental neural network (M–SOINN) technique and adaptive neuro-fuzzy inference system (ANFIS) technique were proposed for fault detection [76] & [77]. However, this strategy requires fine-tuning of the parameters, which increases the complexity of programming since more powerful hardware is required to implement such methods. This in turn, increases the implementation cost.

Advanced intelligent algorithms such as Ant Colony Optimization (ACO) [78], Artificial Bee Colony (ABC) [79], Grey Wolf Optimization (GWO) [80] and Simulated Annealing (SA) [81] were adopted to achieve GMPPT. Although these optimizations presented good performance in identifying and capturing GMPP under PSCs, complex processes are needed to fine- tuning of their parameters. Furthermore, to implement such algorithms, sophisticated embedded systems are required, which in turn increases the implementation cost. In addition, these algorithms require a significant number of samples to identify the GMPP which reduces the convergence speed.

It seems clear from the literature that the algorithms using two phases to achieve GMPP are the most effective. Firstly, the section containing the GMPP is identified, then one of the conventional algorithms such as P&O or IC is used to track the optimal point [39] & [70]. Including most of the above details, a detailed analysis of MPPT techniques is given in Table 1.

5. Conclusion

This paper provided a summary of the proposed MPPT techniques to deal with the formation of multiple MPPs in the PV panel characteristic as a result of the PSCs. The information mentioned in the previous studies was used to identify the features of the proposed techniques, and to evaluate their performance in reaching the GMPP. In short, all the proposed techniques were able to deal with the multiple MPPs condition and to determine and reach the GMPP. Depending on this study, researchers can identify the appropriate technique to use in their applications. The weighting in selecting the appropriate technique is related to the features that are important in the application, for example, when a high convergence speed is required, it is preferable to use the skipping mechanism technique or modified firefly algorithm. When simplicity and flexibility of the implementation are the most important, it is more likely to use PSO, while if the accuracy is the most important, it is preferable to use ABC or GWO.

Table 1. Analysis of MPPT techniques

MPPT technique	Features
• Perturbation and Observation (P&O) • Hill climbing (HC) • Fractional open circuit voltage • Fractional short circuit current • Switching ripple correlation • Sliding mode control • Incremental conductance (IC) • Constant voltage	- Conventional MPPT techniques. - Low complexity. - Able to find MPP under uniform radiation conditions. - Not able to find GMPP under PSCs.
• Improved IC algorithm	- Able to capture the GMPP under PSCs. - A wide range of data, which are the electrical parameters of the PV panels, is required.
• Extremum seeking control technique	- Has a rapid dynamic response. - Requires more information about the electrical parameters of the PV panels.
• Distributed MPPT (DMPPT)	- Compensation for power loss due to PSCs. - Requires an increase in the number of converters
• Fibonacci sequence-based technique	- Low complexity. - Not able to find GMPP in all cases.
• Trapezium algorithm	- Improve the convergence speed. - Possibly does not find GMPP if the chosen voltage step is incorrect.
• Voltage window search algorithm	- High convergence speed. - Not able to find GMPP in all cases.
• Search-skip-judge approach (SSJ)	- Able to capture the GMPP under PSCs. - Low convergence speed.
• Particle swarm optimization (PSO)	- Able to capture the GMPP under PSCs. - Low complexity. - Computationally intensive and time-consuming.
• Genetic algorithm (GA)	- Able to capture the GMPP under PSCs. - Complex and requires a long computation time to capture the GMPP
• Modified PSO method	- Able to capture the GMPP perfectly under PSCs. - Convergence speed to GMPP lower than PSO.
• Ant Colony Optimization (ACO) • Artificial Bee Colony (ABC) • Grey Wolf Optimization (GWO) • Simulated Annealing (SA) • Simulated annealing algorithm	- Able to capture the GMPP under PSCs. - High convergence speed. - Suitable initial parameters are required - Complex processes are needed to fine-tune their parameters.
• Fuzzy logic (FL)	- Able to capture the GMPP under PSCs. - High performance. - Low convergence speed.
• Cuckoo search • Grey wolf optimization • Bat algorithm (BA)	- Able to capture the GMPP perfectly under PSCs. - High convergence speed. - High complexity.
• Firefly algorithm (FA)	- Simple computational processes with low power disturbance. - Low complexity. - May not find the GMPP.
• Modified firefly algorithm	- Able to capture the GMPP under PSCs. - Low complexity. - Medium convergence speed.
• Hybrid algorithm based on modified firefly and P&O algorithms	- Able to capture the GMPP perfectly under PSCs. - High performance. - Good convergence speed.
• Artificial neural network (ANN)	- Able to capture the GMPP under PSCs. - Needs prior training on the PV modules being used.
• General Regression Neural Network (GRNN)	- Able to capture the GMPP perfectly under PSCs. - High performance. - Requires a sophisticated embedded system - Low convergence speed

Author contributions

Fuad Alhaj Omar: Coordination, preparing literature review, Analyzing, Formatting, and Writing. **Nihat Pamuk:** Checking references, Auditing, and Preparing the structure. **Ahmet Afşin Kulaksiz:** Supervising and Writing-Reviewing.

Conflicts of interest

The authors declare no conflicts of interest.

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