A new method for intermediate power point tracking for PV generator under partially shaded conditions in hybrid system

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ABSTRACT

The tracking of the Intermediate Power Point is more important than the Maximum Power Point when the photovoltaic system becomes a part of a hybrid power generation system. It means that the photovoltaic system can either work on the Maximum Power Point or on the Intermediate Power Point. An optimized control technique for hybrid power generation system is developed in this study to work in both cases with high accuracy and good efficiency, under normal or partially shaded conditions. This technique is based on the combination of two algorithms, the particle swarm optimization algorithm for tracking the global maximum power point, while a newly developed algorithm is used for attaining any other supervisory control set point. Furthermore, the new proposed algorithm has the advantage of choosing the point of highest voltage and lower current among the other points that provide the same power, which would increase the efficiency of the system by reducing the power losses. A simulation work is carried out to assess the effectiveness of the proposed technique. Different scenarios under normal and partially shaded conditions are verified. Finally, the combined control algorithm was implemented using a DSpace 1104 environment and extensively tested under various partially shaded patterns. The experimental results of the prototype have proven that the newly developed algorithm improves the capability of photovoltaic system to respond quickly and precisely to the supervisor of the hybrid power system under different partially shaded conditions.

1. Introduction

The integration of the PV system in the hybrid power generation system has strengthened its position as an alternative source and overcome its drawbacks. In the literature, different combinations were proposed and analyzed for grid-connected and stand-alone modes. These include PV-Battery, PV-Wind-Battery, PV-Fuel cell, PV-Wind-Diesel, PV-Fuel cell-Battery, PV-Wind-Diesel-Battery-Fuel cell (Halabi et al., 2017; Ahmadi and Abdi, 2016; Khare et al., 2016; Khan et al., 2017; Maleki and Askarzadeh, 2014; Hosseinalizadeh, 2016; Isa et al., 2016), where the PV system is expected to have advanced controllability and would ensure more flexibility. Since the extracted power exceeds the consumption, due to the load/grid and/or the energy storage system (ESS), the following bad consequences would appear in stand-alone or grid-connected modes (Sangwongwanich et al., 2016): (1) Voltage increase in the coupling points (Luna et al., 2017); (2) Overloading the grid which would lead to overvoltage and frequency instability; (3) Instability in the hybrid system when the DC-bus voltage increase, (4) The intermittency caused by repeated restarts of the PV system for avoiding the previously mentioned problems, accelerate the degradation of the switching devices (Yang et al., 2014). Thus, it can be concluded that the renewable energy sources (RESs) in general and the PV system in particular have to operate in two modes: maximum power mode (MPM) and limited power mode (LPM). The first mode is applied when the load and ESS were able to receive the whole extracted power. On the other hand, when the ESS is at its maximum level and the load demand is lower than MPP’s captured power, the limited power mode will be applied (Zerkcouai et al., 2011).

Based on the above-mentioned approaches, it appears that even though tracking the maximum power point is mandatory for the PV system, working in limited power becomes an obligation, especially in the case of hybrid power generation system (HPGS).

In literature, various techniques and methods have been proposed for tracking the maximum power point, either with or without shading.
conditions, the new ones have been classified and compared in (Ramli et al., 2017; Liu et al., 2015; Ram et al., 2017; Rezk et al., 2017). Under uniform irradiation case, the authors in (Ram et al., 2017), driven by the need of increasing the power and the efficiency of PV system, have created an intelligent maximum power point tracking (MPPT) method by optimizing the Hopfield neural network (HNN) with a fuzzy logic controller (FLC). From the same purpose, the conventional methods, like perturb and observe (P&O) and incremental conductance (IC), were combined with artificial intelligence algorithms, as artificial neural network (ANN) and fuzzy logic controller (FLC), for developing hybrid methods, which have improved the performance of the PV system, especially in its steady state. Due to their fixed step size, the conventional methods are often trapped in local maximum point on shading conditions (Ram et al., 2017). In the non-uniform irradiation mode, which has attracted more interest recently, almost all the artificial intelligence algorithms like ANN and FLC are able to track the global maximum power point (GMPP). However, since they required massive training during the complex environmental conditions, bio-inspired maximum power point tracking algorithms considered as a good alternative in this special conditions, where the evolutionary algorithms and swarm intelligence based algorithms are considered as the successful and predominant classes. Furthermore, combining the bio-inspired algorithms with the conventional ones leads to more precise results, especially in terms of reducing oscillations and convergence speed (Li et al., 2018; Lian et al., 2014). Even in their study (Ram and Rajasekar, 2017), the authors have considered that the flower pollination algorithm (FPA) is suitable for MPPT applications among the other bio-inspired techniques, the particle swarm optimization (PSO) technique is increasingly preferred and prompts researchers in recent studies (Dileep and Singh, 2017; Ram and Rajasekar, 2017), to modify the standard version to meet the practical consideration of their systems.

In spite of growing research interest in the MPM, the LPM has not received the same attention, despite its importance in the power management of hybrid renewable energy systems (HRES), where it has been overlooked in some proposed HRES. For example, In Roumila et al. (2017), the energy management of hybrid system wind-photovoltaic-diesel with storage battery has been proposed. In the diverse operation modes that have been considered, the excess PV power has been always sent to charge the battery, without considering the battery state of charge. In Tiar et al. (2016), a PV-fuel cell hybrid system has been proposed, the PV module is considered as the main source, where the fuzzy logic controller was used to track the maximum power point under normal irradiance shapes. Meanwhile, the excess power was injected into the grid, without considering the fact that the grid would not be always able to receive all delivered power. In few works, the LPM has been only used to enhance the performance of the PV system. In Yang et al. (2014), within the proposed hybrid MPPT-CPG control concept (CPG: constant power generation), the limitation mode is solicited to reduce the temperature of the switching devices and increasing the utilization factor of the PV inverters. Application of this mode also lead to avoidance of the intermittency of PV grid connected system by working continuously in the limited power more. In Sangwongwanich et al. (2016), the previous MPPT-CPG control algorithm has been developed to minimize the power losses and overshoots of the grid-connected PV system. While the LPM concept has been established under different names in some recent HRES research projects (Choudar et al., 2015; Golsorkhi et al., 2017; Kim and Bae, 2017; Karimi et al., 2017), when the extracted PV power is more than the power demand and all batteries are fully charged, The authors in Choudar et al (2015) proposed the PV power limitation strategy to reach the limitation power, which is requested when the storage units are full and the PV generated power is greater than the grid demand, to keep the grid-connected active PV system (APS) in stable operation inside a microgrid. The applied power limitation algorithm was based on the perturb and observe technique, with the comparison of the limited power reference and the actual power at each cycle. Work in

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**Table 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power ($P_{in}$)</td>
<td>80 W</td>
</tr>
<tr>
<td>Voltage at maximum power point ($V_{max}$)</td>
<td>17.7 V</td>
</tr>
<tr>
<td>Current at maximum power point ($I_{max}$)</td>
<td>4.52 A</td>
</tr>
<tr>
<td>Open circuit voltage ($V_{oc}$)</td>
<td>21.9 V</td>
</tr>
<tr>
<td>Short circuit current ($I_{sc}$)</td>
<td>5 A</td>
</tr>
<tr>
<td>Number of cells</td>
<td>36</td>
</tr>
</tbody>
</table>

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**Fig. 1.** Equivalent circuit of solar cell.

**Fig. 2.** Series-parallel combination of solar cells.

**Fig. 3.** The P-V curves for sun earth solar power TBD125x125-36-P module with varying irradiance.

Golsorkhi et al. (2017) used a PV curtailment and load shedding for protecting the storage system units from deep discharging and over-charging. Similarly, in Kim and Bae (2017), once the charge rate of the energy storage surpasses the predefined threshold value, the PV generator shifts to power regulation mode. A decentralized power management to share the load among the hybrid PV/Battery units has been addressed in Karimi et al. (2017), among the operating states of the units that has been considered in this system, PV power curtailment state, in which, the sum of the loads and all batteries charging capacity is less than total PV maximum power. However, in the last three systems, only the way of calculating the limited power reference was clarified, without presenting the control technique details. Finally, from the above-mentioned works, it can be concluded that, the LPM has been applied in the power management in some of the aforementioned
works, but its usage was limited only on the normal irradiance shapes.

In this paper, a new control technique for switching from the MPM to the LPM is proposed, which permits the PV system to work either in a maximum power point (MPP) or in an intermediate power point (IPP) and, moreover, under normal or partially shaded conditions. Also, it would have the advantage of choosing the last right point that exists among the other point having the same power which has the highest voltage and the smallest current. The proposed technique uses the conventional PSO algorithm for tracking the global maximum power point (GMPP) under partial shading conditions. The new algorithm is used for attaining any other set point. That will be determined by the supervisory control system of the HPGS.

The remainder of this paper is structured as follows: Section 2 briefly presents the model of the solar PV and that of the array, while the role of the by-pass diode in the shaded modules is detailed in Section 3. Section 4 describes the partial shading effects on the PV array while Section 5 presents an overview of the algorithms that track the MPP and further details of the PSO algorithm. Section 6 describes the proposed algorithm. The persuasive results that confirm the accuracy and quickness of the proposed algorithm in reaching the IPP are presented in Section 7. Finally, Section 8 summarizes the main findings and the contribution of this work.

2. Modeling of solar PV array

2.1. Modeling of solar cell

In the literature, several models have been used to present solar cell, most of them are based on a single or a double diode model (Park and Choi, 2015). However, the one diode model is the most adopted (Adhikari and Li, 2014; Villalva et al., 2009). The equivalent circuit of this model is depicted in Fig. 1 it is modeled of the solar irradiance current $I_{irr}$, a diode to model the p-n junction and two resistances. The shunt resistance $R_{sh}$ is related to the manufacturing method of the solar cell, it shows the effect of the leakage current of the p-n junction, while the series resistance $R_s$ is related to the contact resistance between the metal and the semiconductor.

The relation between the output voltage $V_{pv}$ and the output current $I_{pv}$ is given by the following equation:

$$I_{pv} = I_{pv,0} \left( \frac{V_{pv}}{V_{therm}} \right) ^ {n} \left( 1 - \frac{V_{pv} + R_s I_{pv}}{V_{therm}} \right)$$

where $I_{pv}$ is the photocurrent under the Standard Test Conditions (STC, 25 °C and 1000 W/m²), $V_{therm}$ is the thermal voltage of the cell, $k$ is the Boltzmann constant ($1.3805603 \times 10^{-23}$ J/K), $T$ is the temperature of the p-n junction, $q$ is the electron charge ($1.60217646 \times 10^{-19}$) and $n$ (1 ≤ $n$ ≤ 1.5) is the cell ideality factor.

The photogenerated current $I_{pv}$ is linearly related to the irradiance level and the temperature of the cell by the following equation (Tian et al., 2012):

$$I_{pv} = I_{pv,0} \left( \frac{G}{G_0} \right) [1 + K_T(T-T_0)]$$

where $I_{pv,0}$ is the photogenerated current under the Standard Test Conditions (STC, 25 °C and 1000 W/m²), $G_0$ is the relative temperature coefficient of the short-circuit current, $G$ and $T$ are the solar irradiance and the cell temperature at STC respectively, $G$ is the actual solar irradiance and $T$ is the actual cell temperature.

The solar cells are connected in series and parallel as shown in Fig. 2 to form a specific PV panel with the appropriate parameters, with the number $N_c$ cells in series and $N_p$ cells in parallel, Eq. (1) becomes:

$$I_{pv} = N_p I_{pv,0} \left( \frac{1}{V_{therm}N_c} \left( \frac{V_{pv}}{N_c} + \frac{R_s}{N_p} \right) \right) \left( \frac{V_{pv} + R_s I_{pv}}{N_c} \right) \left( \frac{N_p}{N_p} \left( \frac{V_{pv}}{N_c} + \frac{R_s}{N_p} \right) \right)$$

The parameters of the PV module that used in the simulation studies are shown in Table 1. Hence, the $P-V$ characteristics of this module
In order to meet the specified PV power which is mostly higher than the power of a single module, the modules can be just connected in series to form a string. This will increase the open circuit voltage of the string to become equal to $N_{ss} \times V_{OC}$, where $N_{ss}$ is the number of series connected modules and $V_{OC}$ is the open circuit voltage of the PV module. In the second case, the modules are connected in series and parallel to form a PV array, hence, the open circuit voltage is calculated as before, while the short circuit current is equal to $N_{pp} \times I_{SC}$, where $N_{pp}$ is the number of parallel connected modules and $I_{SC}$ is the short circuit current of one module.

Fig. 4 shows the connection arrangement of series-parallel modules; it can be seen that they are arranged in parallel strings to form a PV array. Moreover, two diodes have been added for an important role, the blocking diode would prevent the current of the parallel strings or the

![Diagram of PV array](image)

**Table 2**

<table>
<thead>
<tr>
<th>Voltage range</th>
<th>Current value</th>
<th>Current source</th>
<th>Current path</th>
</tr>
</thead>
<tbody>
<tr>
<td>3Voc - 2Voc</td>
<td>$I_{p3}$</td>
<td>P3</td>
<td>$I_{p3}$ flows through P1, P2 and P3 for different voltage ranges</td>
</tr>
<tr>
<td>2Voc - Voc</td>
<td>$I_{p3} + I_{p2}$</td>
<td>P3 and P2</td>
<td>$I_{p2}$ flows through P2 and P3</td>
</tr>
<tr>
<td>Voc - 0 V</td>
<td>$I_{p3} + I_{p2} + I_{p1}$</td>
<td>P3, P2 and P1</td>
<td>$I_{p1}$ flows through P1 only</td>
</tr>
</tbody>
</table>

In order to meet the specified PV power which is mostly higher than the power of a single module, the modules can be just connected in series to form a string. This will increase the open circuit voltage of the string to become equal to $N_{ss} \times V_{OC}$, where $N_{ss}$ is the number of series connected modules and $V_{OC}$ is the open circuit voltage of the PV module. In the second case, the modules are connected in series and parallel to form a PV array, hence, the open circuit voltage is calculated as before, while the short circuit current is equal to $N_{pp} \times I_{SC}$, where $N_{pp}$ is the number of parallel connected modules and $I_{SC}$ is the short circuit current of one module.

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current of an external source to flow back to the panels. Whereas, the task of the by-pass diode, which is connected in parallel with each PV module, will be detailed in the next section.

3. Role of by-pass diode in the PV shaded modules

The PV modules are connected in series-parallel to match the specified PV array output voltage and power. The current generated by these modules is directly proportional to the irradiance level that they received. Thus, during partially shaded condition, the shaded modules produce less current than the unshaded ones, whilst the same current must flow through the series connected modules in the string. As a result, the shaded module(s) will operate in the reverse bias region in order to conduct the current of unshaded modules, which would

Fig. 7. I (panel and diode)-V and P-V curves of PV array under partial shading.
dissipate a part of the energy generated by this latter. On the other hand, the reverse bias voltage may reach the breakdown voltage which leads to the thermal breakdown of the cell, and causing the creation of hot spots. While excessive heating leads to an open circuit in the hole PV array. Fig. 5 shows graphically how the shaded module has to work with a bias voltage to flow the current of the string. This drawback has been solved by the insertion of by-pass diode, which will prevent the reverse bias voltage to reach the breakdown voltage. Also, it becomes the second path to conduct the overcurrent generated by the unshaded modules of the same string (Ahmad et al., 2017; Bidram et al., 2012).

4. Partial shading effects on PV arrays

4.1. By-pass diode current effects

In order to explore the effects of the partial shading on the PV array, it is preferable to begin by explaining this effects on one string. Fig. 6 depicts the currents, the voltages, and the power of a string contains three modules (P1, P2, and P3), it is assumed that P1 is fully illuminated, while P2 is partially shaded and P3 is fully shaded as shown in Fig. 6a. The string’s current will be analyzed according to the open-circuit voltage of the PV panels, as detailed in Table 2.
the second string, the same current value, from which it can be concluded that the position of the modules, even their modules of the same shading intensity have di
spectively, it can be seen that both strings generate the same currents, the
second string respectively are fully illuminated; the module P11 is
form an Array. The third modules (P13 and P23) of the
Fig. 7a three strings (three modules of each) are connected in parallel to
At the voltage
Voc
panels P21 and P22, over the whole open circuit voltage of the string.

After understanding the operating principle of the PV string under partial shading conditions, and the role of the by-pass diodes, it is essential to analyze the shading effects on the PV array itself. As shown in Fig. 7a three strings (three modules of each) are connected in parallel to form an Array. The third modules (P13 and P23) of the first and the second string respectively are fully illuminated; the module P11 is heavily shaded; while the other modules are slightly shaded. By comparing Figs. 7b and 6b which show the values and the current paths of the first string of actual PV array and the previously studied string respectively, it can be seen that both strings generate the same currents, even their modules of the same shading intensity have different location, from which it can be concluded that the position of the modules has no effect, as long as they are exposed to the same shading level. For the second string, the same current value I_{P22} is delivered by the two panels P21 and P22, over the whole open circuit voltage of the string. At the voltage Voc, the unshaded module starts producing its own current, causing the activation of the two by-pass diodes of the shaded modules, which begin conducting the excess current. The three modules of the third string have the same shading intensity; therefore, they produced the same current throughout the string voltage, as illustrated in Fig. 7e.

Fig. 7f shows the current of the PV array, which is the sum of the strings’ currents, while the power of this latter and those of strings are presented in Fig. 7g. Since the modules of the third string receive the same irradiance, they generate the same current and no by-pass diode has been activated, which led to the exhibition of only one local maximum (LMA). However, as the second string is disposed to two irradiance level, two by-pass diodes were activated simultaneously, and as a result, the second LMA has been developed between 0(V) and Voc. While, for the first string, since the three modules receive three different irradiance level, it exhibits three LMs. Therefore, despite the number of LM in the second and the third string, the PV array develops three LMs.

Based on Figs. 6d and 7g it can be concluded that the global maximum (GM) can be one of the LMs, as it will be detailed in the next section, where the array will be replaced by a string for simplicity of the analysis.

4.2. Global maximum point

Fig. 8a and b show three strings receiving three different irradiance intensity and their corresponding P-V curves consecutively, the first module P1 of the second string is fully illuminated, the second one is slightly shaded, while the third one is heavily shaded, under this irradiance levels, the corresponding P-V curve shows the GM in the middle. In the case of the first string, the second and the third modules continue receiving the same irradiance level, while the first module starts receiving high irradiance intensity compared to the two other modules, which result in pushing the GM to the right as shown in Fig. 8(b1). Meanwhile, between the second and the third strings, the change was seen in the third module, where the irradiance level becomes a bit higher than it was in the second string, while the two other modules still exposed to the same irradiance intensity, which drags the GM to the right side as presented in Fig. 8(b2). Thus, it can be concluded that the number of local maxima is equal to the number of modules that have different shading level. While the position the global maximum point is related to the difference in the irradiance intensity.

5. Tracking of maximum power under partial shading

Harvesting the maximum energy from the PV system is an easy way to improving its efficiency as long as it generally relies on the implemented algorithm. This needs to deal quickly and accurately with the atmospheric conditions changing and with the partial shading operations (Kheloud et al., 2016). Since the conventional maximum power point tracking (MPPT) algorithms (Perturb and Observe (P&O), Incremental Conductance (IC) and the Hill Climbing (HC)) are not able to cope with non-uniform irradiance and reaching the GM, the soft
computing techniques (Fuzzy Logic Controller (FLC), Artificial Neural Network (ANN) and Evolutionary Algorithms (EA)) become an adequate alternative, especially with their ability to deal with the problems encountered during partial shading. Principally, the PSO is one of the evolutionary algorithms which based on search optimization to locate the GM and more suitably used under partial shading conditions (Ishaque and Salam, 2013). The working principle of this technique will be presented in the following sub-section.

5.1. Overview of practical swarm optimization (PSO)

For reaching the maximum power point of the PV array in partially shaded condition, the particle swarm optimization (PSO) technique is highly efficient because of its simplicity, fastest operation and its easy implementation (Ishaque et al., 2012). In addition, it requires less computation compared to other artificial intelligence techniques (Alajmi et al., 2011; Elobaid et al., 2015).

PSO is an intelligent search mechanism, it has a swarm of candidate solution called particles. Each particle has a position in the search space of the optimization problem and by communicating the data obtained after successive iteration of all particles, they proceed towards the best solution.

Each particle of the swarm has:

(a) Position ($X_i$): the actual position of the particle
(b) Velocity ($V_i$): it describes the movement of the particle in the sense of direction and distance.
(c) Best particle ($P_{best,i}$): the best position experienced by the article

Fig. 12. Intermediate power point in partial shading mode.

Fig. 13. IPP tracking steps during partial shading with zoom.
The numerical values given to the previous parameters in the implementation are: $\omega = 0.4$, $c_1 = 1.2$ and $c_2 = 1.4$, which were determined by using trial and error method (Miyatake et al., 2007).

5.2. PSO based MPPT technique

The first step for using PSO in tracking the MPP is to define the population size, which is the number of particles. These particles can be duty cycles or voltages. While, in the case of uniform isolation, the voltages could be chosen near to MPP for reaching this point with less number of iteration. However, in the case of partial shading, as it was proved in (Ahmad et al., 2017), the number of local maxima (LM) is equal to the number of the series-connected module in a string, that have different irradiance intensity. Thus, the population size would be equal to the number of LM and the initial value of each particle would be near to the MPP of LMA for the same reason explained before.

The flowchart below (Fig. 10), summarizes the different steps of this algorithm, while Fig. 11 shows the movement of the three particles P1, P2, and P3, they have started moving from their initials values until they reach the global maximum point.

6. Limited power mode operation

This mode can be applied either when the PV system works alone or integrated into a hybrid system, as well as in standalone or grid-connected mode. However, the limited power mode becomes mandatory when the PV extracted power could not be consumed by the loads or stored by the ESS.

In case of uniform irradiation, the intermediate power has two same power points: one by left and one by the right. However, under partial shading conditions, the number of IPP is related to the power value and to the number of the local maximum point, which it can be ranging from two points to twice the number of LM points as shown in Fig. 12. Fig. 12a shows that there is a considerable difference between the current/voltage of the first IPP at the left side and the last point on the right. The current is decreased whenever the voltage is increased. In this scenario, by using the last operating point on the right side, the desired power is attained with low current and high voltage. Interestingly, the power loss would be significantly diminished for the switching devices and for the conducting wires. As a result, the converter efficiency will be sensibly increased. For this purpose, it is desired that the proposed algorithm will always choose point corresponding to largest possible voltage and minimum possible current on P-V characteristic for the PV array.

6.1. Intermediate power point tracker algorithm

For each time when the PV system received the limited power reference, the new initial values of the PSO particles would be calculated according to the equation below:

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Summary of the new features of the IPPT algorithm and their advantages.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Features/Capabilities</td>
<td>Tasks/Advantages</td>
</tr>
<tr>
<td>Capacity of locating any intermediate power point</td>
<td>In many situation, the PV system needs to operate under the maximum power, even in grid-connected or standalone applications</td>
</tr>
<tr>
<td>Ability of working under partially shaded conditions</td>
<td>Partial shading becomes unavoidable situation</td>
</tr>
<tr>
<td>Capability of switching from the maximum power mode to the limitation power mode and vice versa</td>
<td>Facilitates the integration of the PV system in hybrid power generation system</td>
</tr>
<tr>
<td>Capability of choosing the IPP of the largest possible voltage and the lowest possible current</td>
<td>Reduces the switching devices and conducing wires losses</td>
</tr>
<tr>
<td>Zero steady state oscillations</td>
<td>Increases the efficiency of the PV system</td>
</tr>
<tr>
<td>Simple algorithm with very fast execution time</td>
<td>Possibility of implementation in low-cost microcontrollers</td>
</tr>
<tr>
<td>Very fast tracking speed</td>
<td>Important for high dynamic response applications</td>
</tr>
</tbody>
</table>
where $V_{oc}$ is the open circuit voltage of the string, the constant value “0.65” represents the minimum appropriate percentage of the open circuit voltage of the module, from which it can be its MPP and $N_{scm}$ is the number of series connected modules in the string. With these initial voltages, the power near to LM of each module could be sensed. Once the corresponding power of the three initial voltages has been measured, their values will be compared with the intermediate power reference. The point which has the highest voltage and whose power is greater than the reference power becomes the new initial value ($V_{a}$) of the IPPT algorithm.

The developed algorithm starts by the selection of the endpoints of the searching interval. The voltage $V_{a}$ represents the first point of the interval. The second endpoint ($V_{b}$) would be the $V_{oc}$ of the PV array. It could be the corresponding voltage to the smallest power delivered by the PV system.

The second step in the algorithm is IPP tracking. This part is based on the successive division of the interval $[V_{a} V_{b}]$ to find the midpoint $V_{c}$, by following Eq. (7), and comparing the power of this point with the intermediate power reference.

$$V_{c} = V_{a} + \frac{V_{a} - V_{b}}{2}$$  \hspace{1cm} (7)

The new $[V_{a} V_{b}]$ interval has been determined according to the comparison between the $V_{c}$ point’s power and the intermediate power reference (IPR). If this power is greater than IPR, the point $a$ takes the voltage value of the point $c$. Otherwise, the voltage of the midpoint becomes the voltage of the point $b$. Then, repeatedly bisects the new interval and selects the subinterval according to the previous rule until the reference power is reached. Fig. 13a depicts the power of the initial voltages and the tracking of the IPP. From the four points with the same power (85 W), the program has successfully oriented to the point with the highest voltage as expected. Fig. 13b shows clearly the four intervals and the three performed division to reach the expected result. The flowchart shown in Fig. 14 recaps the important steps of the IPPT algorithm. While the new features/capabilities of this latter, with their main advantages are outlined in Table 3.

### 7. Experimental results

The experimental verification of the combined algorithms, PSO with IPPT algorithm was carried out based on the circuit shown in Fig. 15. The PV array output was generated by the Programmable DC Power Supply, Chroma 62150H-1000S, the PV array simulator, while the control algorithms have been implemented in DSpace CP1104 –TMS320F240 DSP platform. Fig. 16 shows the I-V and the P-V curves of the PV array under partial shading, where a profile with two local and one global maximum has been programmed. The PSO and IPPT algorithm have been applied to track GM of 214 W and the IPP of 150 W respectively. The experimental results of the tracking voltage and current are depicted in Fig. 17. At the start, the PV operated at 145 W, which correspond to $V = 80$ V and $I = 1.8$ A. As it can be observed, at the instant $t = 5.6$ s, the PSO algorithm started tracking the GM. After 1 s, the GM has been reached and the system kept working at this point, at the moment $t = 12.5$ s, the IPPT algorithm is initiated to track the appropriate IPP among the six point of the same power as they are presented in Fig. 16. As can be observed clearly in Fig. 17, within five
Fig. 17. Experimental waveforms: Voltage (a) and Current (b).

Fig. 18. Current and power of the PV simulator with GM in the left side.

Fig. 19. Current and power of the PV simulator with GM in the right side.
Fig. 20. Experimental waveforms: Voltage (a) and Current (b) of left GM pattern.

Fig. 21. Experimental waveforms: Voltage (a) and Current (b) of right GM pattern.
steps (0.2 s), the proposed technique precisely tracks the limited power of the highest voltage and lowest current. Moreover, the greatest advantage of the proposed algorithm is its capability of eliminating the steady-state oscillations to zero after reaching this limited power, as shown in Fig. 17a.

7.1. Practical robustness test of IPPT algorithm

For ensuring the robustness of the IPPT algorithm, two more shading patterns were proposed, as can be clearly seen in Figs. 18 and 19, the rated and intermediate powers of both new proposed pattern are different from the first case, where the GM was in the middle. The intermediate power of the first pattern (Fig. 18) is 120 W while the second pattern (Fig. 19) is 230 W, the crucial importance of the first pattern lies in large gap between the GM’s voltage and that of the intermediate power as it can be seen in Fig. 18 however, in the second pattern, on the contrary, both voltages are near to each other as presented in Fig. 19.

The voltage and the current of the left GM pattern are shown in Fig. 20. As it was chosen in the first case, the start operating voltage was fixed at 80 V, which is corresponding to the power 125 W. At the instant t = 8 s, the PSO algorithm was triggered to track the GM, it has been reached within half second, as a result, the voltage decreased to 33 V. After remaining five seconds in the maximum power, the IPPT algorithm is activated to track the point of the intermediate power, that has the highest voltage among six points of the same power. In less than fifth second, the IPP has been accurately located and the voltage jumped to 102 V, as can be clearly seen in Fig. 20a these results highly confirm the robustness of proposed algorithm and affirm its accuracy, particularly with zero oscillations in the voltage after attaining the limited power, despite, on one hand, the large gap between the GM and IPP voltages and, on the other hand, the different voltages of the same intermediate power.

Once again, as it can be seen in Fig. 21 after the launching of the PSO at the instant t = 2.4 s, that has reached the GM in almost one second, the IPPT algorithm started tracking the IPP under the right GM pattern five seconds later, which has been reached in very short time (0.2 s) and with appreciable accuracy, with a power of 230 W and a corresponding voltage of 107 V. Refer to Fig. 19 it can clearly notice the greater inclination in the slope of the P-V curve between the voltages of GM and tracked IPP, this reaffirms once more the robustness of the IPPT algorithm.

Finally, in a detailed and structured way, the obtained results from the three partial shading scenarios are summarized in Table 4. All values of currents, voltages, and power are given, including the start tracking and arrival time for both modes, which leads to easily verify the short duration of the shifting time from one mode to another.

It can be seen from Table 4 that, for shifting from the start working voltage of 80 V to the GMPP voltages, which are corresponding to the three shading patterns of the left, the middle and the right global maximum points, and match with the values 33/65/100 V respectively, the PSO technique tracking time was 0.95/1/0.9 s for the three patterns successively. While for moving from those voltages to IPP voltages 102 V/108 V/107 V, the IPPT algorithm took only 0.2 s for the three patterns, which represent approximately one-fifth of the PSO technique tracking time. Moreover, the difference between the powers of the true IPPs and of the reached points are 2.4/1.2/10.75 W or 2/1/4.5% of the output powers, where less accuracy it can be seen for the right pattern, due to the small difference between GMPP and the IPP voltages, nevertheless, this did not prevent the IPPT algorithm to locate the IPP. Therefore, the obtained results are closely matching desired test conditions, where the strengths of the proposed technique are proved by its very fast tracking speed, its effectiveness and accuracy, and with the soft and the fast change of mode, thus proving new proposed method’s usefulness for incorporation in hybrid power generation system, and for allowing energy harvesting under wide range of shading conditions.

8. Conclusion

In this paper, a PV system under partially shaded condition has been controlled to move smoothly between the maximum and limited power mode. Here, a PSO has been used for the first mode, while the IPPT developed algorithm has been used for the second mode. The newly proposed algorithm has the advantage of tracking the intermediate power under normal or partially shaded conditions with faster speed and null steady state oscillations. Additionally, it could track the IPP on the left or right side. Meanwhile, due to the exhibited advantages, the right side has been chosen in this work, in addition, the robustness of this new algorithm has been confirmed, through its capability of reaching the required point under three different location of the GM point, on the left, in the middle and on the right. As verified experimentally, for shifting from the start working power, which corresponds to the voltage value of 80 V for the three shading patterns, to reaching their GMPPs that matches with the voltages 33/65/100 V, in the left/middle/right order consecutively, the PSO algorithm took 0.95 ± 0.05 s. While for moving from GMPPs to the IPPs (102/108/107 V), the tracking time for proposed algorithm was only 0.2 s. Moreover, the IPPs tracking efficiency achieved an average percentage of 97.5% of the powers of the true IPPs. Thus, the proposed method yields good results in reaching the intermediate power accurately, with null oscillations and in very fast tracking time. This achievement ensures to the proposed PV system its ability to be a part of a hybrid power generation system, and meet their requirements under partially shaded conditions.

References

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