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Maximum power point tracking of partial shaded photovoltaic array using an evolutionary algorithm: A particle swarm optimization technique

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Partial shading is one of the unavoidable complications in the field of solar power generation. Although the most common approach in increasing a photovoltaic (PV) array's efficiency has always been to introduce a bypass diode to the said array, this poses another problem in the form of multi-peaks curves whenever the modules are partially shaded. To further complicate matters, most conventional Maximum Power Point Tracking methods develop errors under certain circumstances (for example, they detect the local Maximum Power Point (MPP) instead of the global MPP) and reduce the efficiency of PV systems even further. Presently, much research has been undertaken to improve upon them. This study aims to employ an evolutionary algorithm technique, also known as particle swarm optimization, in MPP detection. © 2014 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License. [http://dx.doi.org/10.1063/1.4868025]

I. INTRODUCTION

Compared to other means in harvesting renewable energy, photovoltaic (PV) systems can be said to possess several fundamental advantages.[1,2] For example, their application of semiconductor devices makes the solar energy they collect a static, quiet, and movement-free energy source, ensuring the system's longevity and low-maintenance costs. Conversely, the power yield is often diminutive, such that the individual use of PV modules is not recommended. Usually, both, series and parallel configurations of PV modules are utilized to provide the load with the required voltage and current.[3–7] Using bypass diodes on the related configurations of PV modules, on the other hand, would produce the conditions of partial shading; whose detrimental effects on PV array efficiency still persist despite recent advancements in technology. Specifically, partial shading would alter the output of the array such that it results in a nonlinear power-voltage relationship and multiple peak characteristics, the latter of which decreases the efficiency of the conventional Maximum Power Point Tracking (MPPT) methods.[8–11]

Previous researches have managed to conceive appropriate MPPT methods to track the maximum point with minimum deviations. Perturbation and Observation, Incremental Conductance and hill climbing are the most frequently applied and well-designed of these methods used in finding the maximum power point (MPP) at a uniform insolation level.[12–16] However, they are less than ideal such that, in the presence of shading, their precision in pinpointing the MPP becomes undermined.[17–19]

Studies have been undertaken to design an appropriate controller, by examining the Global tracking method during disruptive conditions.[17,20–22] In the course of these efforts, the

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conventional MPPT methods have also been improved upon, through the use of lengthy calculations. However, the research in question was constrained to a specific PV array configuration under certain partial shading patterns. In this paper, the evolutionary algorithm termed Particle Swarm Optimization (PSO) will be used to derive the Global MPP in a multi-peaks function.[23–26] It will also be applied to three simulations with disparate settings so as to assess its performance in contrasting conditions.

II. MODELING

The modeling of PV systems has been extensively described in previous studies.[27–31] Among the many constructions of PV module circuitry, the "General" model shown in Fig. 1 is regarded as an accurate and less complex form. The exponential variables of the module while operating at an irradiance level of S and temperature of T_k can be calculated using Eq. (1),

$$P(I_{pv}, V_{pv}) = \left(I_{ph} - I_o \left[\exp\left(\frac{q(V_{pv} + I_{pv}R_s)}{N_s A K T_k} \right) - 1 \right] - \frac{(V_{pv} + I_{pv}R_s N_s)}{R_p N_s} \right) \times (V_{pv}), \quad (1)$$

in which I_{ph} and I_o are the solar-generated current and the diode saturation current, respectively. q refers to the Electron Charge constant, K the Boltzmann constant, and A the Diode ideality factor. The number of cells connected to the series circuit is indicated by N_s, while the numbers of those in parallel are symbolized by N_p. Fig. 2 represents the I-V and P-V characteristics of the BP SX 150s PV module for different insolation levels. The manufacture specification of stated module can be obtained from Table I.

III. PARTICLE SWARM OPTIMIZATION

A. The basic PSO algorithm

Particle Swarm Optimization is an example of evolutionary Algorithms. It investigates the Search-Space, and can be used to determine the components and settings required to optimize an especial Objective Function.[32] The operation begins with a random selection, continues with a search for optimal solutions through earlier iterations, and evaluates the solution qualities through the fitness. The PSO algorithm is suited for the derivation of the global optimum. It is also simple in principle, and has a high tracing accuracy as well as fast convergence.

As described earlier, the PSO algorithm first selects a number of particles, given as N, at random from a D dimensional search space; the dimension, D, is determined by number of decision variables. Every particle represents one candidate solution, each running stochastically with a certain speed (Vi) in the search space. The movements of particles are in accordance with their best (P_{bi}) position and their Global best (G_b) position. To be more precise, P_{bi} is the best position experienced by the ith particle throughout all previous iterations, while G_b is the best position experienced by the sum of all particles within all past iterations.

During the optimization process, the particles adopt the objective function's values, whilst their G_b and P_{bi} are recorded. The basic PSO algorithm which defines the next position of the candidate solution is as follows:
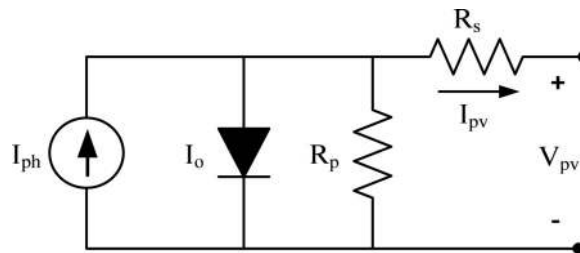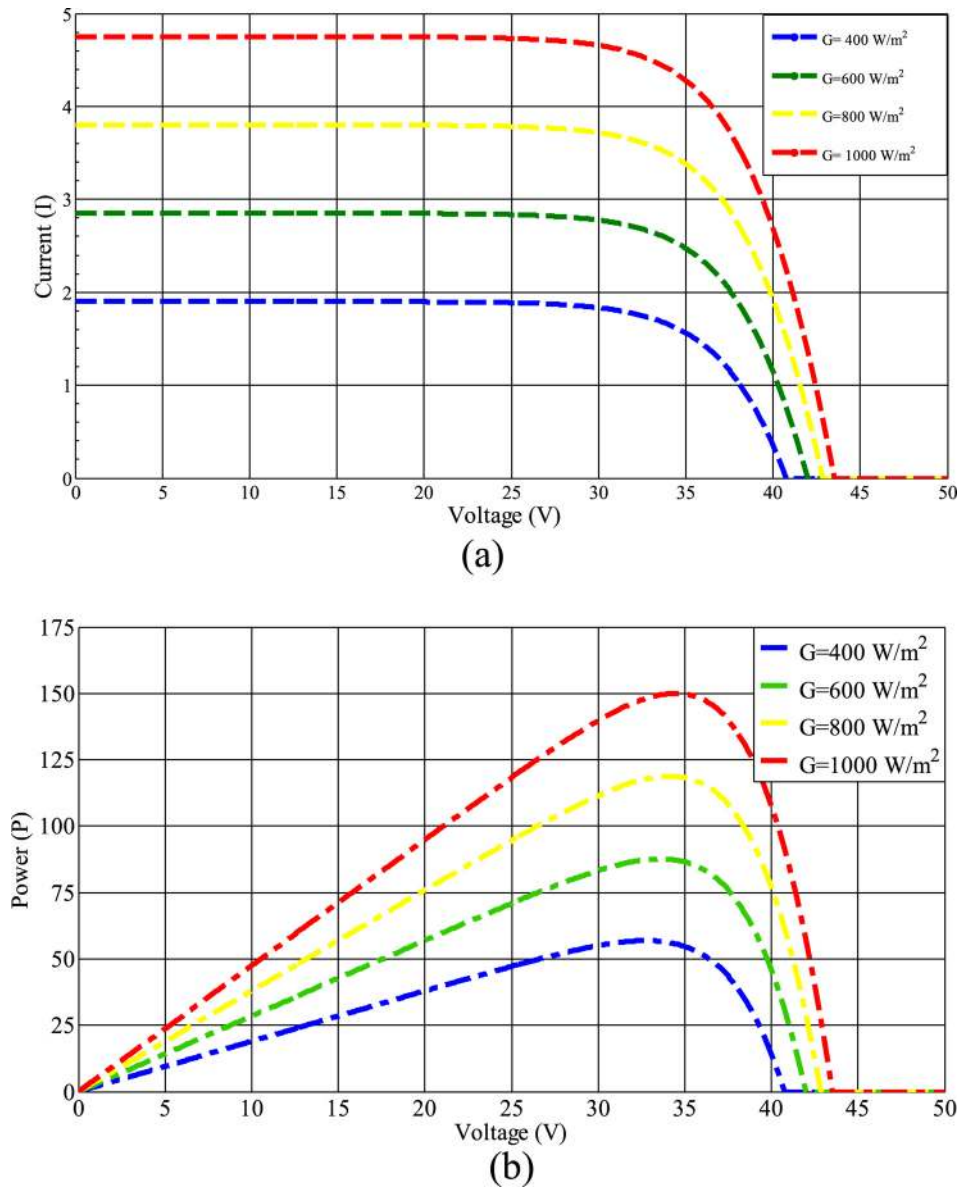

FIG. 1. Equivalent circuit of photovoltaic cell.

FIG. 2. Output characteristics of PV module in difference irradiance levels. (a) I-V and (b) P-V.

TABLE I. PV module specification.

Electrical characteristic	BP SX 150s
Open circuit voltage	43.5 V
Short circuit current	4.75 A
Maximum power voltage	34.5 V
Maximum power current	4.35 A
Maximum power	150 W

$$V_i^{k+1} = w \times V_i^k + r_1 \times c_1 \times \left(P_{bi} - X_i^k\right) + r_2 \times c_2 \times \left(G_b - X_i^k\right), \tag{2}$$

$$X_i^{k+1} = X_i^k + V_i^k, \tag{3}$$

wherein i represents the variable of the optimization vector, k is the number of iterations, Vi^k and X_i^k the velocity and position of the ith variable within k iterations, w the inertia weight factor, c_1 the cognitive coefficient of individual particles, c_2 the social coefficient of all particles, and r_1 as well as r_2 are the random selected variables in the range [0, 1]. The main purpose of these random parameters is to maintain the stochastic movement within iterations. To keep the search space in a certain area, the values of the velocity are set to the range of [0, $Vmax$].

As mentioned, the variable P_{bi} records the best position assumed by the ith particle up to the exact time of measurement. Equation (4) indicates that this position is only recorded as P_{bi} if the condition stated below is satisfied,

$$P_{bi} = X_i^k \quad If \quad F\left(X_i^k\right) \geq F(P_i). \tag{4}$$

B. Design of PSO parameters

In particle swarm optimization, the parameters w, c_1, and c_2 are highly mutable. The slightest change in their values may affect on the speed and accuracy of the algorithm. The optimization may involve in the local maximum by any poor design for c_2 and its accuracy can be diminished by the inappropriate value for c_1. Similarly, the influence of the inertia weight on the speed and convergence of PSO is also substantial; as the large value for this parameter results in a slower convergence while small value brings about a narrower range of search space. Therefore, it may be concluded that a shift in the inertia weight's values, encourage the diffusion of the particles at its initial stages before gradually limiting the search space in the final iterations. The behavior of the inertia weight's values is shown in Fig. 3, whereas the parameters' values in PSO are documented in Table II.

C. PSO based MPPT

The search space of the problem is a one-dimension space in which each location represents a voltage value as a solution to the MPPT problem. The evaluation of the particles is based on the output power of the PV panel respective to the proposed terminal voltage value
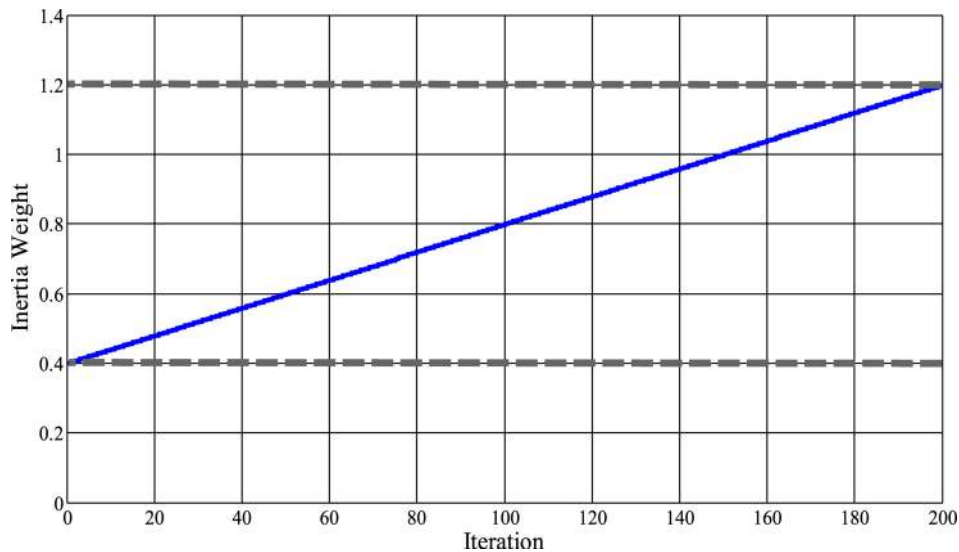

FIG. 3. Behavior of inertia weight during all iteration.

TABLE II. Parameters values of PSO.

C_1	C_2	w	r_1 and r_2
2	1.5	1.2	[0–1]

which is denoted by F as the fitness evaluator for the particles. Equation (5) shows the location matrix of the N particles which represents N solutions to the MPPT problem, at the same time,

$$X_i^k = \left[X_1^k, X_2^k, X_3^k, \ldots, X_i^k, \ldots X_{(N-1)}^k, X_N^k \right],$$ (5)

where X_i^k is the location of ith particle at kth iteration. From a practical point of view, the generated power fluctuates due to variations in the insolation levels and degree of partial shading.
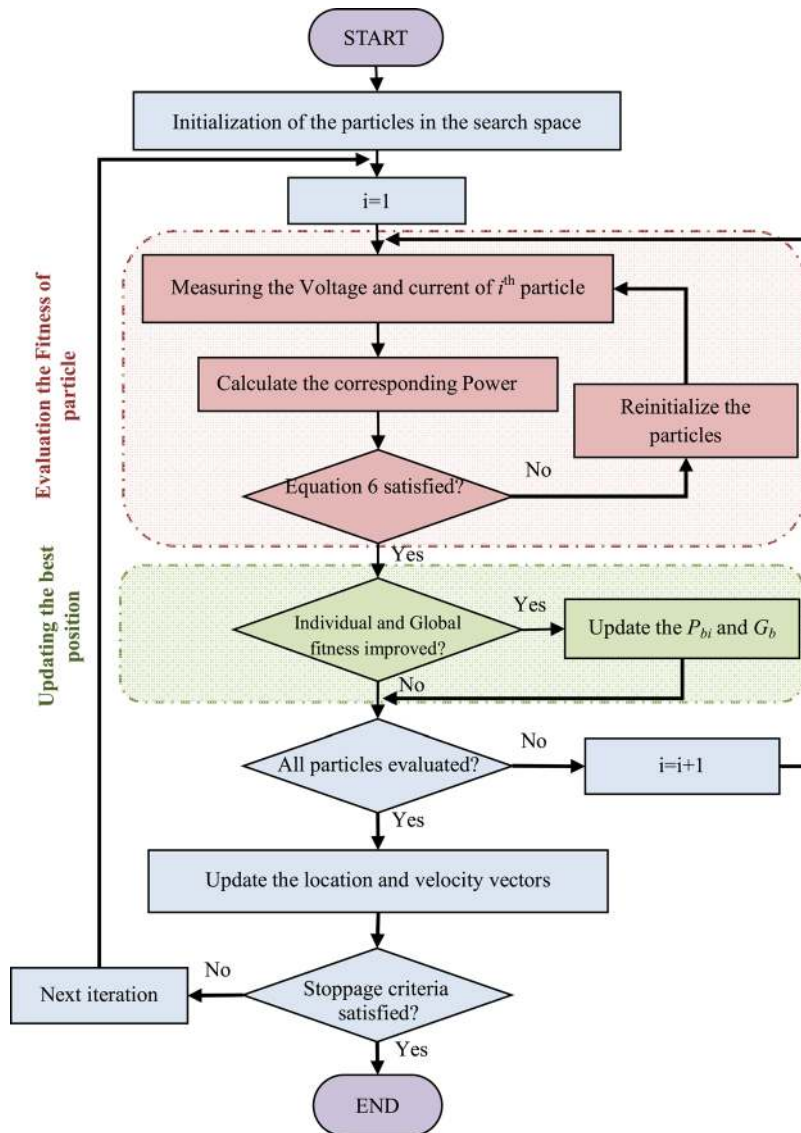

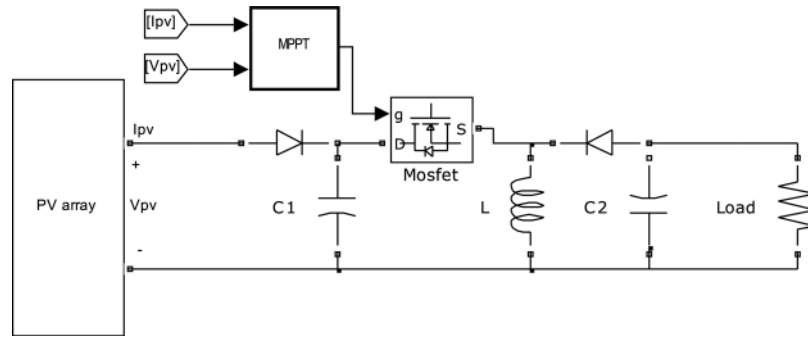FIG. 4. The fellow chart of PSO based MPPT control algorithm.

FIG. 5. Model of PV array connected to the buck-boost converter.

Therefore, the algorithm must be initialized when Eq. (6) is satisfied. If this step is neglected, the acquired values of P_{bi} and G_b should not be considered their actual values,

$$\left| \frac{F(X_{i+1}) - F(X_i)}{F(X_i)} \right| > \Delta P. \tag{6}$$

The implementation strategy of the proposed MPPT technique is briefly described in the flowchart of Fig. 4. In the flowchart, the constraints refer to the maximum and minimum possible of the voltage which can be set for the voltage converter. In this study, voltage of the PV array can be set from zero to Voc depending on the configuration of the array.

IV. SIMULATED CONDITIONS

In this section, the simulations of three different cases with varying degrees of partial shading are presented, to validate the performance of the proposed method in different partial shading conditions. The simulation is carried out using MATLAB software with parameters listed in Table I. The MATLAB/Simulink model of the PV system with buck boost converter used in this study is presented in Fig. 5. The switching frequency of the converter is set to 20 kHz and it designed according to the following parameters: C2 = 220 μF, C1 = 470 μF, and L = 1 mH.

The PSO algorithm was applied to these conditions separately, to evaluate and verify its functionality with respect to irregular insolation levels. In accordance with the design guidelines presented in Sec. III, the parameter settings of the PSO algorithm are listed in Table III. In this paper, the cell temperature is assumed to be constant, at 25 °C for all conditions, but irradiance levels are varied different conditions.

A. First condition

Fig. 6 shows the circuitry for an array consisting of two modules in a series arrangement. Each module has the same circuit topology as shown in Fig. 1 and is connected parallel to a bypass diode. Using Eq. (1), if the first module receives the irradiance level, S1 of 1000 W/m^2, and the second one an irradiance level, S2 of 350 W/m^2, the resulting P-V and I-V correlation of the array will be as shown in Fig. 7. The pre-set conditions for this case exemplify a moderate level of partial shading. Since the global peak occurs earlier than local peaks, the actual

TABLE III. The output result of PSO algorithm in three conditions.

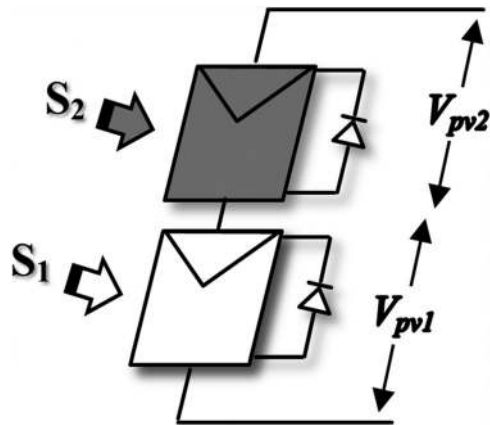| Test condition	$I_{M(exp)}$	$V_{M(exp)}$	$P_{M(exp)}$	$P_{M(pso)}$	$I_{M(pso)}$	$V_{M(pso)}$	P_{EE}
First condition	4.35	34.6	150	149.6	4.3	34.3	0.99
Second condition	2.5	71.2	179	178.1	2.4	71.3	0.98
Third condition	2.1	71.7	150.4	150.1	2	71.6	0.99

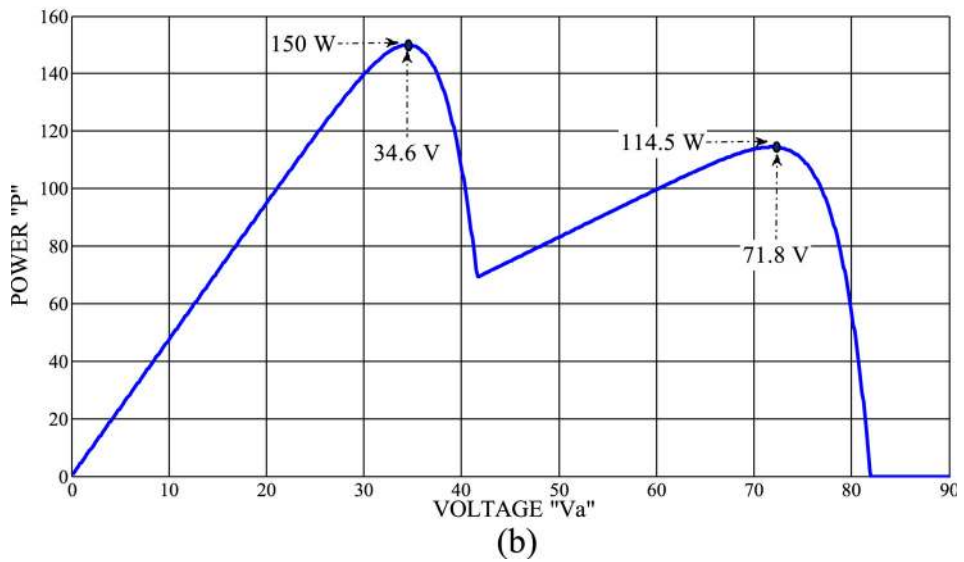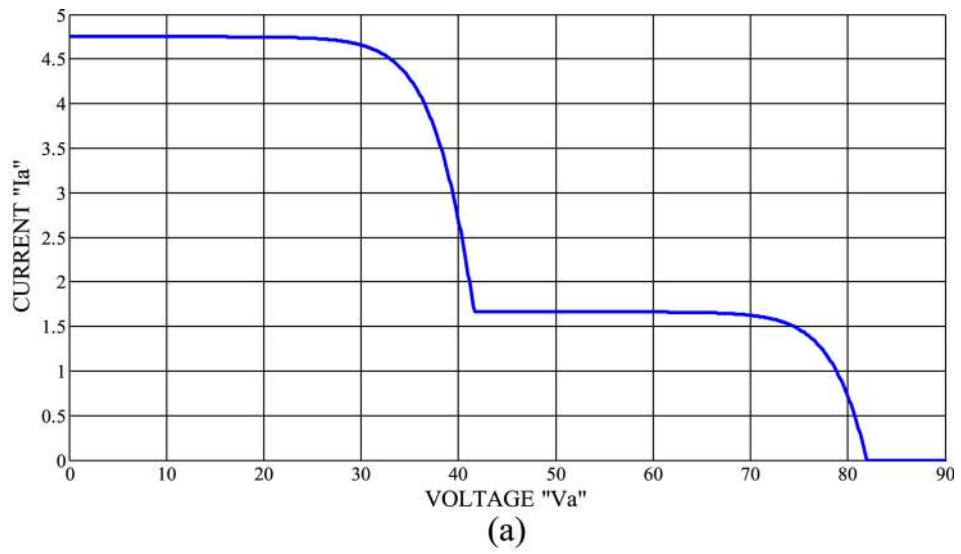FIG. 6. PV array configuration for first partial shading condition.

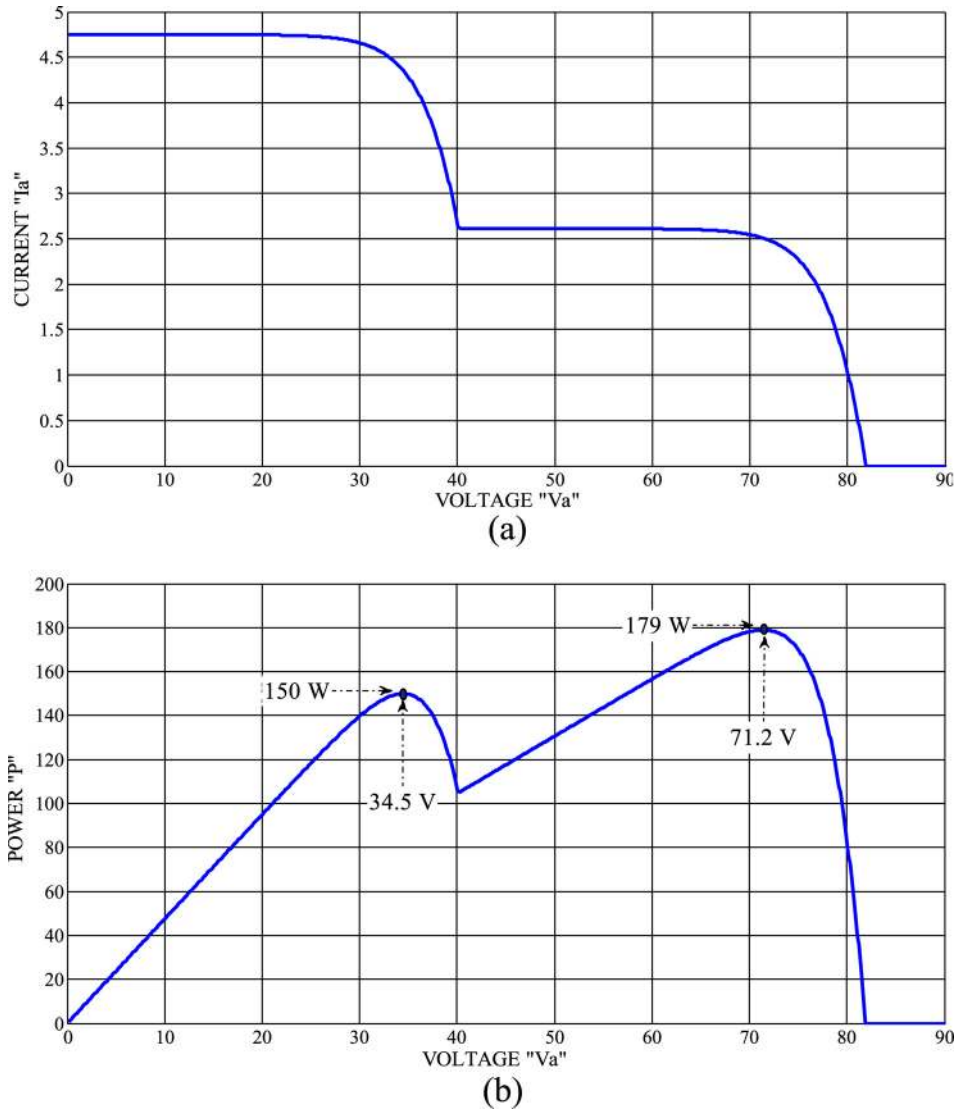FIG. 7. Output characteristics of PV array under the first condition. (a) I-V and (b) PV.

FIG. 8. Output characteristics of PV array under the second condition. (a) I-V and (b) P-V.
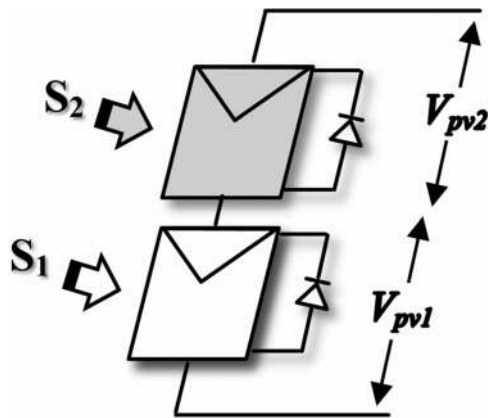

FIG. 9. PV array configuration for second partial shading condition.

MPP can be obtained even with the traditional MPPT techniques. This is because the conventional methods are often concerned with the first peak, which basically attunes them to finding the Global MPP under the aforementioned conditions.

B. Second condition

The second case is largely similar to the first, but differentiates from it in that there is a huge difficulty in using the conventional MPPT methods; as the global MPP now occurs after the local. Fig. 8 shows the output characteristic of the PV array shown in Fig. 9, while the first and second modules receive the irradiance levels $S_1 = 1000 \, W/m^2$ and $S_2 = 550 \, W/m^2$, respectively.

C. Third condition

The objective behind this particular simulation lies in the assessment of the PSO algorithm's accuracy when the majority of the array falls under shadow. Of significance is the minute difference between its derived Global MPP and the two other corresponding values. Fig. 10 shows the circuit model of an array composed from three PV modules in a series configuration. If the individual modules receive the irradiance levels of S1 = 1000, S2 = 7000, and S3 = 500 separately, the resultant output characteristics of the entire PV array is as featured in Fig. 11.

V. RESULTS AND DISCUSSION

Fig. 12 shows the power locus of the proposed approach along with output P-V characteristics for all three conditions. As found in Fig. 12(a), the controller first finds the local MPP in its early operation, and it trails the global MPP, following a few iterations. The end result shows that the planned MPPT tracker is capable to monitor the global maximum point in a relatively short time, even under mismatched conditions. The system is verified in second condition, which is known as a more critical partial shading pattern. Fig. 12(b) demonstrates that the presence of the neighboring MPP prior to the Global MPP doesn't prevent the controller from reaching the ideal power point.

The true functionality of the PSO algorithm is further demonstrated by applying this algorithm to a triple peaks objective function, as shown in Fig. 12(c). The slight difference between the local maximums and global maximum did not reduce the accuracy of the PSO in finding
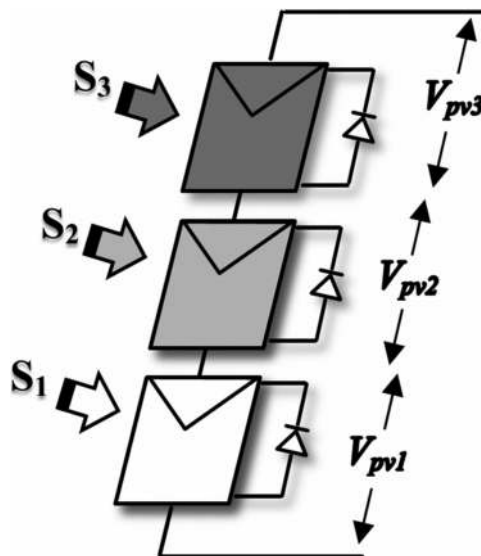

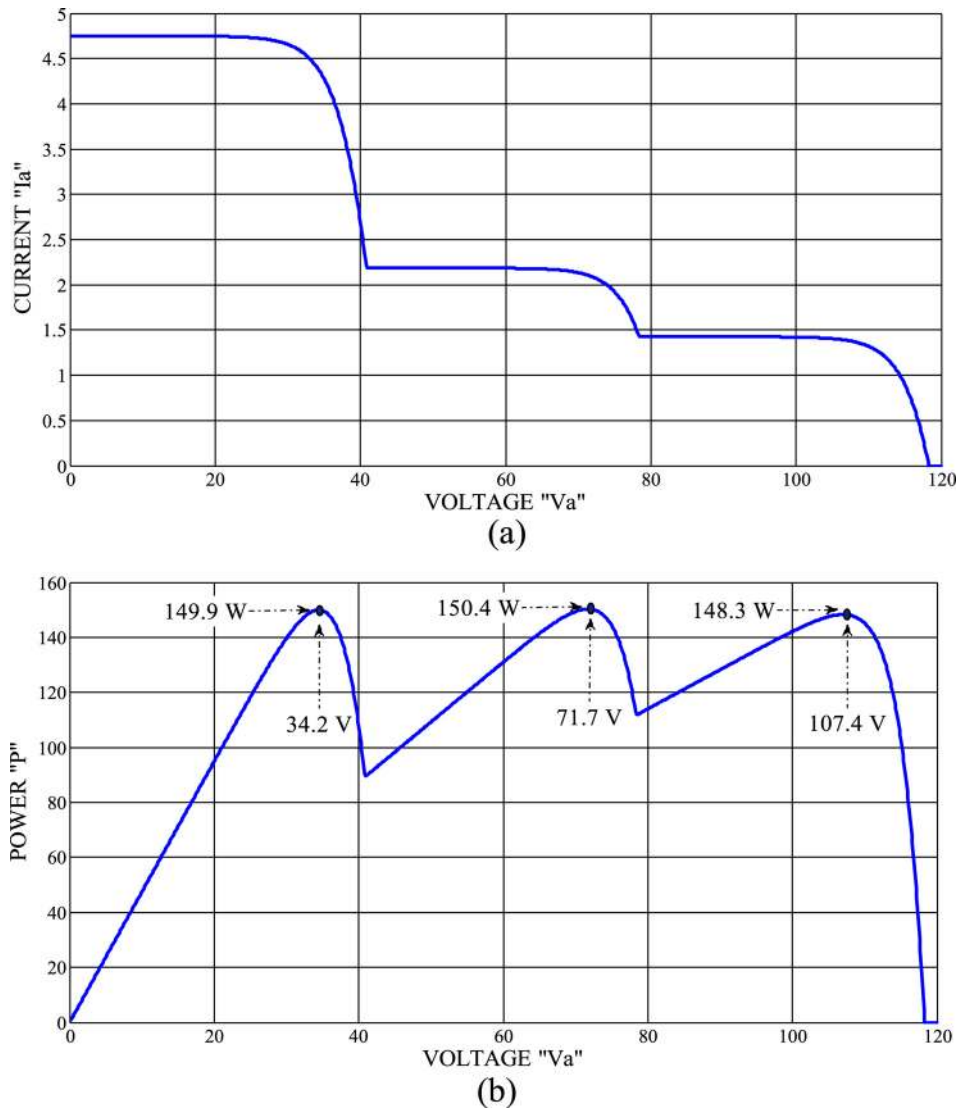FIG. 10. PV array configuration for third partial shading condition.

FIG. 11. Output characteristics of PV array under the third condition. (a) I-V and (b) P-V.

the actual MPP. The concept of PSO is clearly illustrated in the simulation results of all three predetermined case studies. For instance, in the early iterations, the wider range of search space is covered by the proposed algorithm, as the value of inertia weight (w) is in the minimal spectrum. On the other hand, the limited range of search space is being focused, as the value of inertia weight (w) reaches its maximum value throughout the final iterations. Although it doesn't completely prevent the PSO algorithm from searching the whole range of the search space even in its final iterations.

Normally, the initialization of the algorithm is achieved by using predefined particles, but in this study, random numbers have been used to initialize the first population of the algorithm. Table III indicates the output results of the applied PSO algorithm for 10 numbers of particles in three simulated conditions. The value of energy efficiency (P_{EE}), which is the portion of generated power tracked by PSO (P_T), and the actual generated power (P_a), is considered as one of the evaluations of the PSO in Table III.

In general, a higher number of agents results in truer MPPT even under acute shading patterns. It must be held that a larger population leads to a gradual convergence speed. Taking the above factors into account, an appropriate number must be used to ensure good tracking speed
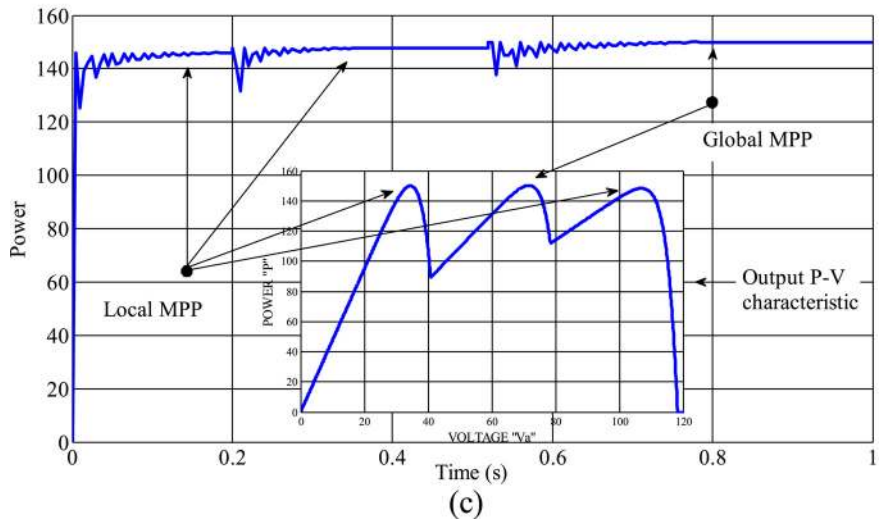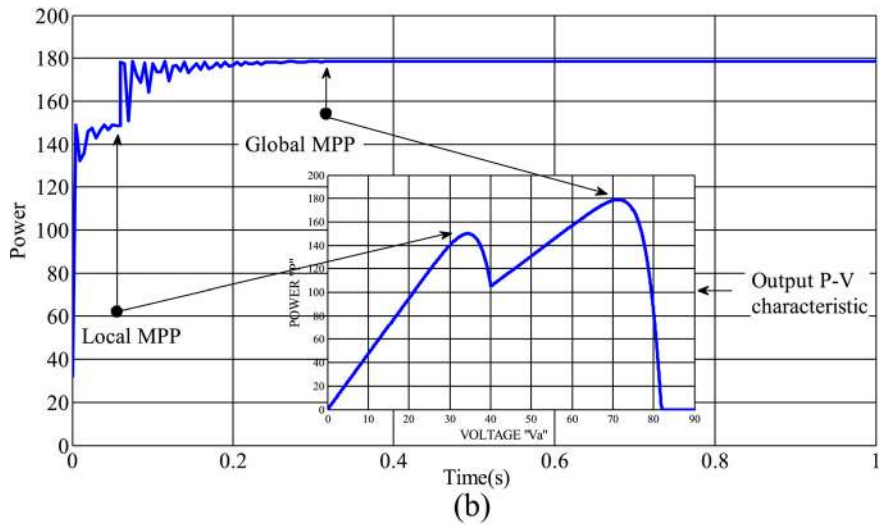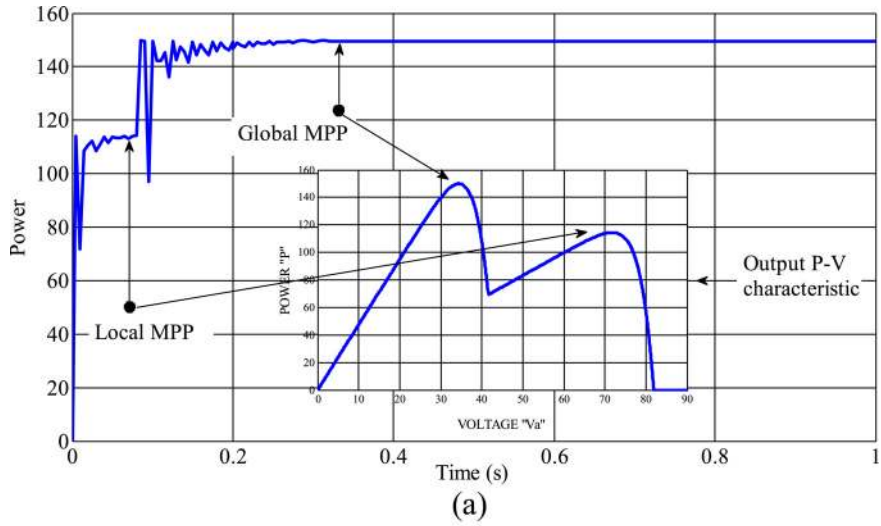
FIG. 12. Output results of proposed method. (a) First condition, (b) second condition, and (c) third condition.
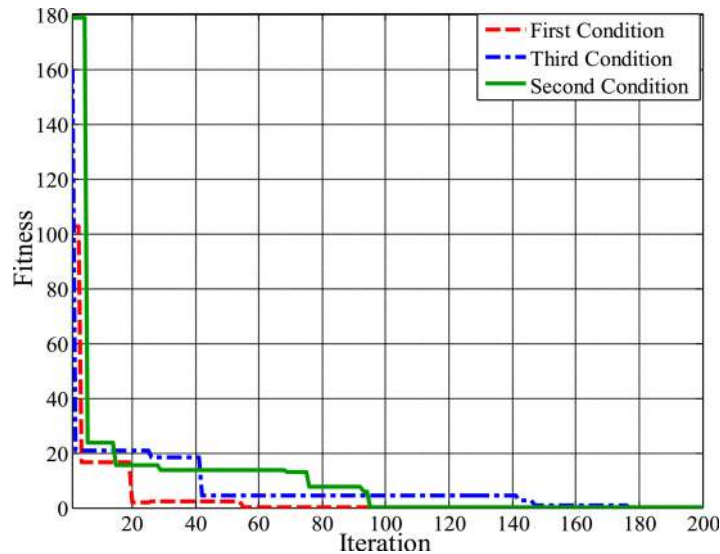
FIG. 13. Convergence of PSO in three conditions.

as well as high accuracy in maximum power tracking. To evaluate the function of the proposed methods during the all iteration performed in one execution of the program, the algorithm convergence for all three conditions is shown in Fig. 13. Although the tracking period in the third condition takes a longer time when compared to first two conditions, it is considered a rapid performance in such a crucial partial shading condition.

VI. CONCLUSION

This study is aimed to develop an evolutionary algorithm called Particle Swarm Optimization to track the Maximum Power Point of the photovoltaic system under partial shading conditions. The method is suited for the application with stochastic behavior. Three different partial shading conditions are defined to verify the reliability and accuracy of the system during partial shading conditions. The final results in first two conditions prove the reliability of the proposed system to distinguish the global MPP from local MPP; regardless of their presence at the output of photovoltaic system. In addition, the results for the third condition show the accuracy of the proposed method in finding the actual MPP, when there is a slight difference between global MPP and local MPPs. The main advantages of the proposed technique are as follows: (1) the stochastic nature of PSO algorithm made this a purely system-independent MPPT technique. (2) Using the PSO algorithm protects the MPPT, ensuring that it falls into the local maxima during the partial shading conditions. (3) The system is adaptive; as it is initialized by detecting any changes in temperature and irradiance levels. (4) The system is accurate enough to track the global MPP even during acute partial shading conditions.

ACKNOWLEDGMENTS

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