Global maximum power point tracking in partially shaded PV systems using plant reproduction algorithm

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Abstract
The power–voltage curve of photovoltaic (PV) power generation system under partial shading conditions (PSC) is non-monotonic with multiple power peaks and traditional methods do not guarantee global convergence which leads to energy loss. This paper proposes a new tracking scheme for global maximum power point (GMPP) on a shaded PV system based on plant reproduction algorithm (PRA). The concept of PRA is suitably tailored towards maximum power point tracking (MPPT) and lucidly explained in this work. The algorithm is applied towards MPPT in several shaded PV architectures through computer simulations and later verified through experimentation. Computed and measured results show that PRA quickly identifies GMPP and further provides significantly improved MPPT characteristic curves compared to established alternatives.

1 | INTRODUCTION

Increased demand of electricity and declining fossil fuel deposits, have encouraged the use of various renewable energy sources. Among the renewable energy sources, photovoltaic (PV) power generation has been accepted as a promising source of energy since solar energy as fuel is omnipresent and freely available; further the PV system possesses static operation, almost negligible maintenance and long life. The major drawbacks of a PV power plant include higher initial investment and influence of climatic conditions on the PV power generated. In order to enhance the revenue from PV power generation, maximum power point tracking (MPPT) scheme is generally integrated with PV power plants. Under uniform solar insolation, the power-voltage (P–V) curve of the PV system has a single power peak and is easily tracked using perturb and observe (P&O), incremental conductance (INC) and hill climbing (HC) techniques [1, 2]. However, when some of the PV modules receive lesser solar insolation due to shading by adjacent buildings, towers, tall trees etc. non-uniform illumination occurs on the PV plant and this is referred to as partially shaded condition (PSC) [3]. Under PSC, the power-voltage (P–V) curve of the PV system is non-monotonic with several power peaks; the higher power peak is called global maximum power point (GMPP) and the remaining ones are referred as local maximum power points (LMPPs). The use of traditional methods referred in [1, 2] towards MPPT in PV systems under PSC fail to guarantee global convergence and this leads to reduced energy yield [4]. P & O method is most popular since it is lucid and easy to implement. However, traditional P & O method suffers from poor convergence time, PV power during tracking as well as sustained oscillations even after GMMP has reached. Hence, several improved P&O methods have been developed over the years to mitigate these drawbacks [5–7]. However, these schemes are usually employed under uniform irradiance conditions.

MPPT in PV systems under non-uniform illumination has been extensively researched and a few hundreds of papers are available in the literature. These methods can be classified in to four categories [8, 9].

1. Array reconfigurations
2. Different PV system architectures
3. Different converter topologies
4. Modified MPP techniques which are capable of converging to global maximum power point (GMPP)
In the above, the first one to three have several drawbacks such as these are costlier, require more components, and involve complex control and higher switching loss and hence most papers employ the fourth category of MPPT scheme. The fourth category can further be subdivided into three groups as given below:

a. Search algorithm based on P–V and I–V characteristics [10, 11]

b. Use of intelligent techniques [12–14]

c. Use of optimisation algorithms [15–24]

The major drawback associated with the first category is the necessity of complete knowledge of the PV power plant characteristics under various operating conditions including PSC. Further, the PV parameters too vary with ambient conditions and hence this method cannot be generalised. The method given in the sub category (b) makes use of either artificial neural network (ANN) or fuzzy logic concept towards MPPT. While these methods are robust, the major short coming is the necessity of vast data required for training the neural networks and developing rule base for fuzzy logic, which is very strenuous. The third sub category classification given in (c) makes use of biologically inspired optimisation algorithms and the few popular ones are particle swarm optimisation (PSO) [15–18], artificial bee colony (ABC) [19] and ant colony optimisation (ACO) [20, 21]. Among these, PSO has been extensively employed for MPPT in PV systems probably due to the fact that PSO is well established, the control parameters are available in the literature and its wide spread use in other engineering fields also. A review of various optimisation algorithms towards MPPT is detailed in [25, 26]. In addition to these methods, hybrid techniques [27–30] are also well researched and a recent publication [31] throws light on to it.

The above literature survey clearly suggests that numerous MPPT schemes are available in the literature and each method varies in terms of MPPT characteristics such as convergence time, tracking efficiency etc. and ease of implementation. The above survey also shows that attempts are continuously made to find newer algorithms with faster convergence and feasibility of hardware implementation.

In this context, this paper reports a new MPPT algorithm based on plant reproduction cycle which was reported earlier as plant reproduction algorithm (PRA) and is available in [32]. The seed which falls on fertile soil sprouts first, grows faster and produces more seeds; the seeds falling on lesser fertile land grow slowly and produce lesser seeds. The original work in [32] is suitably tailored towards MPPT in PV systems under PSC and limited and preliminary computer simulation findings are presented in [33]. This work is an extension of [33] and proposes PRA as a promising method towards MPPT under PSC. The new algorithm possesses few salient features, which are given below:

- it is simple, easy to understand and implement on a low-cost microcontroller.
- It relies on “survival of fittest” mechanism and guarantees global convergence.
- “Elitism” is embedded on it, thus retaining the best solution so far obtained.
- The new algorithm has a single parameter to be tuned which can be easily done.

The organisation of the paper is given below. Section 2 is dedicated to description of MPPT system. In Section 3, a brief introduction of PRA is outlined first followed by its application towards MPPT in PV systems. This section elaborates the use of the new MPPT scheme in a lucid manner. The computed and measured results are summarised in Sections 4 and 5, respectively. Considering the bulk volume of MPPT schemes available in the literature and wide spread use of PSO as an MPPT scheme, the authors are constrained to compare the results of the proposed work with PSO and traditional P&O methods. The computed and experimentally obtained PRA based MPPT curves are shown to be faster, reliable and far superior to the established alternatives.

2 | DESCRIPTION OF MPPT SYSTEM

This section systematically explains MPPT circuit, PV modelling and PV systems under study.

2.1 | Hardware description

The newly developed MPPT technique is verified through experimental process. A prototype PV system for this purpose was developed in the laboratory and employed for measurements. The schematic of the prototype is shown in Figure 1. This system consists of a PV array, current sensor, voltage sensor, multiplier IC, dc–dc converter, PIC microcontroller and load. The proposed optimisation algorithm is developed in MPLAB and then downloaded to the digital controller. In the closed loop mode, the digital controller generates a duty ratio and activates the boost converter. Once steady state is achieved, the PV voltage and current are sensed and are fed
TABLE 1 Details of the hardware setup

| Component                      | Specification       |
|--------------------------------|---------------------|
| Microcontroller                | PIC16F876A          |
| PV Module                      | Vikram Eldora 20P   |
| IGBT                           | 1MBH15D060          |
| Current sensor                 | LEM55P              |
| Voltage sensor                 | LV 25-P             |
| Switching frequency, \( f_s \) | 50 kHz              |
| Capacitor, \( C \)             | 470 μF              |
| Inductor, \( L \)              | 1.5 mH              |
| Internal resistance of Inductor, \( r_L \) | 0.358 Ω          |
| Load resistance, \( R \)       | 150 Ω               |

2.2 | Modelling of PV system

The single diode model [4] is used to generate the power-duty ratio (P-d) curves. The PV modelling equations under partial shaded condition are given below [9]:

\[
I_{pv} = I_{ph} - I_o \left[ \exp \left( \frac{V_{pv} + R_s I_{pv}}{V_t} \right) - 1 \right].
\]  

(1)

The photo current, \( I_{ph} \) of a solar module is determined using the following equation:

\[ I_{ph} = (I_{sc} + k_i \Delta T) \].

(2)

PV module output voltage, \( V_{pv} \) from (1) when \( I_{ph} \) is greater than \( I_{pv} \) can be written as:

\[ V_{pv} = V_t \left[ \ln \left( \frac{I_{ph} - I_{pv}}{I_o} \right) + 1 \right] - R_s I_{pv}. \]

(3)

2.3 | Modelling of boost converter

Considering the two modes of boost converter [34], the switch is in the ON state for a period of \( dT \) seconds and remains OFF for the remaining \( (1 - d) \) \( T \) seconds, where, \( d \) is the duty cycle and \( T \) is the time period.

The inductor voltage is written as

\[ L \frac{dI_{pv}}{dt} + I \, r_L = V_{pv} - (1 - d) \, V_o. \]

(4)

\[ C \frac{dv_o}{dt} + \frac{v_o}{R} = (1 - d)I_{pv}. \]

(5)

Taking Laplace transform of inductor voltage and capacitor current given in (4) and (5) and denoting \( V_{pv}(s) \), \( V_o(s) \) and \( I_L(s) \) as Laplace transforms of \( V_{pv} \), \( I_{pv} \) and \( v_o \),

\[ LsI_L(s) = V_{pv}(s) - I_L(s)r_L - (1 - d)V_o(s), \]

(6)

\[ CsV_o(s) = (1 - d)I_L(s) - \frac{V_o(s)}{R}. \]

(7)

On rearranging (6) and (7), the following equation can be obtained:

\[ \frac{V_{pv}(s)}{I_L(s)} = \frac{1}{L} \left( s + \frac{r_L}{L} \right) + \frac{(1 - d)^2}{C \left( s + \frac{1}{RC} \right)}. \]

(8)

In the above equation, left hand side represents the input impedance of the PV system for a typical operating point on the P–V curve and the right-hand term is the output impedance. When the climatic condition changes, the value of left-hand variable in (8) changes leading to drifting of new MPP. The MPPT can now be successfully achieved by adjusting the duty ratio, \( d \) of the dc–dc converter, which alters the value of right-hand side term.

2.4 | PV system under study

Numerous PV configurations with a variety of partial shading conditions were considered for computer simulation; however, only two typical cases are discussed here namely five series- two parallel (5s2p) and five series- five parallel (5s5p). The Equations (1)–(3) are used for simulating PV configurations under PSC and the PV power-duty ratio (P-d) curve is plotted using Equation (8). Few PV modules in these configurations are partially shaded as shown in Figures 2(a) and 2(c) leading to P-d curves as shown in Figures 2(b) and 2(d) which are named as pattern 1 and pattern 2, respectively. The details of PV modules are given Table 2. Figure 2(b) has one local power peak of 96.69 W and global peak at 127 W. Further, P-d curve in Figure 2(d) has three local power peaks of 291.2 W, 286.1 W and 211.7 W and global peak of 382.4 W.

Table 2 Parameters of single PV module

| Parameter                  | Value   |
|----------------------------|---------|
| Maximum power (\( P_{max} \)) | 20 W    |
| Open circuit voltage (\( V_{oc} \)) | 21 V    |
| Short circuit current (\( I_{sc} \)) | 1.28 A  |
| Maximum power voltage (\( V_{mp} \)) | 17.2 V  |
| Maximum power current (\( I_{mp} \)) | 1.2 A   |

The capacitor voltage is derived as

\[ \frac{C}{R} \frac{dv_o}{dt} + \frac{v_o}{R} = (1 - d)I_{pv}. \]

(5)
3 APPLICATION OF PLANT REPRODUCTION ALGORITHM (PRA) TOWARDS MPPT IN SHADED PV SYSTEM

3.1 Brief concept of PRA

The plant reproduction algorithm (PRA) described in [32] is computationally simple and easy to understand and implement. The algorithm mimics evolutionary growth of trees/plants under identical conditions of climatic conditions, but depends on soil fertility. Consider a piece of land in which varied degree of soil fertility exists. This is shown in Figure 3(a) where bigger circle A1 indicates increased fertility followed by A2, A4 and A3. Consider seeds of same variety and quality are sowed randomly in this land as shown in Figure 3(b). The seeds which fell on most fertile land A1, sprouts first, grow fast and bigger, and produce more seeds which fall within its proximity of variable radial distance as shown in Figures 3(c) and 3(d). Plant/tree which fell on soil of medium richness will produce lesser seeds with medium size which also fall around it. The seeds which sprout in barren soil may perish. Thus, the pant/tree which happened to sprout in and around most fertile portion grow bigger, produce more seeds which fall nearer to it, and causes more saplings in that region as in Figure 3(e). Thus, more trees/saplings grow around best fertile soil region and others perish or produce less number of seeds. Thus, in each generation, seeds falling to/nearer to fertile portions thrive and this evolutionary growth of plant/tree can be visualised as convergence to most fertile soil. Considering AI and emerging techniques, the strategy block diagram is given in Figure 4.

3.2 Formulation of MPPT as an optimisation problem

As it is observed from the Figures 2(b) and 2(d), that the PV output power is a monotonous function of duty ratio, d of dc–dc converter. Here, the objective is to maximise PV output power by varying the duty ratio, d. This is formulated as given below:

$$\text{Maximize } P_{PV} = f(d),$$

$$\text{Subject to } d_{\text{min}} \leq d \leq d_{\text{max}},$$

where the subscripts min and max indicate boundaries of duty ratio.

3.3 Procedural steps of PRA towards MPPT in PV systems

For the illustration of application of this algorithm towards MPPT, consider a typical power-duty ratio curve of partially shaded PV array as given in Figure 5(a) and let seeds be sowed randomly in the solution space where each seed location refers to duty ratio of boost type dc–dc converter. Corresponding to each duty ratio, PV power can be computed and this PV power is assumed to be equivalent to fertility of soil. Thus, seed 1 germinates and a plant of bigger size grows at that location. Similarly, other seeds too sprout giving saplings of different sizes depending fertility of soil. Thus, depending on location of seed and PV power corresponding to that location, saplings grow to become plants/tress of different sizes. The biggest tree produces more seeds which fall radially around it and so do the
FIGURE 3  Stages of plant reproduction algorithm. (a) Land showing varied degree of fertility. (b) Seeds are randomly sowed in the land. (c) Seeds sprout and size of the plants depend on the fertility. (d) Healthy plant produces more seeds which fall on A1. (e) Crowding of plants on the best fertile soil

FIGURE 4  Strategy block diagram

FIGURE 5  Application of PRA towards MPPT. (a) P-d curve showing seeds randomly distributed in the solution space and plant size depends on power corresponding to each duty ratio. (b) Bigger plant produce more seeds around it than other plants. (c) Crowding of plants occur near to GMPP
other trees too as shown in Figure 5(b). As time advances, these seeds too sprout and the process repeats. It can be seen that as evolutionary growth of plants continues, crowding of plants will occur around global maximum power point (GMPP) of the power curve as shown in Figure 5(c).

However, if the algorithm is permitted to execute in this manner, the population grows with generations. Hence, we have decided to retain the population size by deleting seeds of lower quality in each generation. For this, at the end of each generation, all plants are arranged in ascending order of PV power associated with them and the best plants from the top equal to population alone are considered for next production; others are deleted.

Accordingly, the steps of the algorithm are given below:

1. Sow seeds in the solution space. Let seeds be \( S_1, S_2, S_3, \ldots, S_j, S_k, \ldots, S_N \) where \( N \) stands for population size and let \( d_1, d_2, d_3, \ldots, d_j, d_k, \ldots, d_N \) be the locations.
2. Corresponding to each seed position, compute PV power using Equations (1)–(3) and boost converter model.
3. Seeds germinate and little plants grow in each seed location. Size of plant is made directly proportional to PV power to plant location.
4. The number of seeds, produced by each plant is computed as given below:

\[
N_i = \left( \frac{P_{vi}}{\sum P_{vi}} \right) N,
\]

where \( P_{vi} \) is PV power in the \( i \)th location and denominator is sum PV power by all plants and the fraction is rounded off to nearest integer.
5. Each seed is randomly distributed around the respective tree radially within a distance of \( R \) such that \( R_{\text{min}} \leq R \leq R_{\text{max}} \).
6. The new seeds are allowed to sprout and size of each new plant again depends on PV power corresponding to its position.
7. All plants—new as well old—are arranged in ascending order of size and the top \( N \) plants alone are retained and all other plants are assumed to be perished.
8. Terminate the program, if termination criterion is reached; else go to step 4.

For better understanding, flow chart of the algorithm is given in Figure 6.

In this work, the program is terminated when PV power attained by each plant differs only by 1% in few sequential iterations and dc–dc converter is operated with the optimum plant location.

4 SIMULATION RESULTS

A dedicated computer program is developed for PRA based MPPT in Matlab under partial shaded condition. In order to demonstrate that the algorithm is robust and the results can be generalised, the two partial shading patterns namely patterns 1 and 2 are randomly imposed to the PV system and MPPT simulations were carried out. As an illustration, pattern 1 was made to exist for the first four seconds and then pattern 2 for the next four seconds. The computed results are shown in Figure 7(a). The results show that PRA based scheme takes 0.8 s to reach
FIGURE 7  Simulation results. Tracking curves for pattern-1 and pattern-2 using (a) proposed algorithm, (b) PSO and (c) P&O

the GMPP 127 W for pattern 1 and 1.0 s to reach the global power peak of 382.4 W for pattern 2. For comparison PSO and P&O methods were also employed for MPPT and the results are included in Figure 7. It is evident that while PSO guarantees global convergence it takes 2.7 s and 3.6 s to locate GMPP for patterns 1 and 2, respectively. The P&O algorithm fails to recognise the GMPP and settles to LMPP. Further, it may be noted that the swing in PV output power during PRA based MPPT is significantly lesser compared to PSO based one. The computed results strongly suggest the superiority of PRA based MPPT. It is worth mentioning that the two shading patterns were introduced in a random fashion several times and the computed results are observed to be very much closer to the one shown in Figure 7. The characteristic features of MPPT employing the three methods explained above are summarised in Table 3.

5 EXPERIMENTAL EVALUATION

In order to demonstrate the feasibility of implementation of the proposed plant algorithm towards MPPT, a prototype MPPT scheme as given in Figure 1 was developed in the laboratory and the details are given in Table 1. The values of boost converter are designed based on [34] for obtaining ripple-free output. Two sets of experimental findings are presented in this section; the first uses five series-two parallel (5s2p) PV arrangement as PV array in Figure 1. Opaque sheets of different thickness were placed on different PV modules to create artificial shading patterns. For this configuration, two different shadings were made and the corresponding P-d curves are displayed in Figure 8(a). These are named as patterns 3 and 4 respectively. As is evident from the Figure 8(a), pattern three has GMPP of 36 W and one LMPP at 18 W; pattern 4 has GMPP of 72 W and LMPP of 50 W. It is to be noted that GMPP falls on left side of P-d curve for pattern 1 while it is located on right side with pattern 2. These two shading patterns were made to exist sequentially for 6 s manually. A dedicated program is developed in MPLAB for PRA based MPPT and then the program was downloaded to PIC 16F876A microcontroller. The closed loop MPPT scheme was then made to operate with patterns 3 and 4 and the measured tracking curves are given in Figure 8(b). It is evident that the characteristic features of tracking curves appear to resemble each other with the computed and measured results. The measured results show that the PRA based MPPT scheme converges to GMPP with 0.75 s for pattern 3 and 1.24 s for pattern 4. For comparison, PSO based MPPT was also implemented under identical conditions for patterns 3 and 4 and the recorded curves are given in Figure 8(c). A comparison of the measured results employing the two schemes clearly indicate reduced convergence time and minimum steady state ripples for PRA based MPPT scheme to PSO based approach. For completeness, P&O method was also employed for tracking and respective curves are given in Figure 8(d). It is seen that the P&O method tracks GMPP for pattern 4 while it settles to LMPP for pattern 3.

The second set of experiments were conducted with five series—three parallel (5s3p) PV array with intentional partial shading and two distinct P-d curves thus obtained are given in Figure 9(a) and named as patterns 5 and 6, respectively. It is worth mentioning that GMPP is located at the centre of P-d curve for 5 while it is shifted to right side with pattern 6. MPPT experiments were repeated for these patterns and tracking curves employing the proposed method, together with PSO and P&O schemes are given in Figures 9(b), 9(c) and 9(d), respectively. The tracking curves in Figures 9(b), 9(c) and 9(d) also show the superiority of the PRA based MPPT over the existing techniques. For an immediate reference, salient features of MPPT characteristics are tabulated in Table 4. The numerical values in the table further confirm speedy convergence to GMPP with minimum P-V output power ripple employing
FIGURE 8  Experimental results with 5x3p configuration. (a) P-d curves. Tracking curves using (b) proposed method (c) PSO and (d) P&O. (Scale: power-21W/division)
FIGURE 9  Experimental results with 5x2p configuration. (a) P-d curves. Tracking curves using (b) proposed method (c) PSO and (d) P&O. (Scale: power-15W/division)
TABLE 3  Performance comparison of proposed method, PSO and P&O

| PV Configuration | Shading Pattern with Max. Power from the P-d Curve (W) | Tracking Method | Power (W) | Convergence Time (s) | Tracking Efficiency (%) |
|------------------|--------------------------------------------------------|-----------------|-----------|----------------------|------------------------|
| 5x2p             | Pattern 1  [127]                                       | Proposed method | 127       | 0.8                  | 99.99                  |
|                  |                                                        | PSO             | 127       | 2.7                  | 99.97                  |
|                  |                                                        | P & O           | 96.69     | 1.3                  | 76.13                  |
| 5x5p             | Pattern 2  [382.4]                                      | Proposed method | 382.4     | 1.0                  | 99.98                  |
|                  |                                                        | PSO             | 382.4     | 3.6                  | 99.96                  |
|                  |                                                        | P & O           | 291.2     | 0.46                 | 76.15                  |

TABLE 4  Experimental evaluation of proposed method, PSO and P&O

| PV Configuration | Shading Pattern with Max. Power from the P-d Curve (W) | Tracking Method | Power (W) | Convergence Time (s) | Tracking Efficiency (%) |
|------------------|--------------------------------------------------------|-----------------|-----------|----------------------|------------------------|
| 5x2p             | Pattern 3                                             | Proposed method | 36        | 0.75                 | 99.99                  |
|                  | GMPP: 36 W                                            | PSO             | 36        | 3                    | 99.99                  |
|                  | LMPP: 18 W                                            | P & O           | 18        | 0.8                  | 50                     |
|                  | Pattern 4                                             | Proposed method | 72        | 1.24                 | 99.98                  |
|                  | GMPP: 72 W                                            | PSO             | 72        | 3.1                  | 99.98                  |
|                  | LMPP: 50 W                                            | P & O           | 72        | 3                    | 100                    |
| 5x3p             | Pattern 5                                             | Proposed method | 45.7      | 0.82                 | 99.99                  |
|                  | GMPP: 45.7 W                                          | PSO             | 45.7      | 3.2                  | 99.98                  |
|                  | LMPP: 40 W                                            | P & O           | 31.5      | 0.75                 | 68.93                  |
|                  | Pattern 6                                             | Proposed method | 65.8      | 1.2                  | 99.99                  |
|                  | GMPP: 65.8 W                                          | PSO             | 65.8      | 2.7                  | 99.99                  |
|                  | LMPP: 41.5 W                                          | P & O           | 65.8      | 0.8                  | 100                    |

PRA based MPPT. Further, PRA based MPPT ensures guaranteed convergence to GMPP irrespective of number power peaks as well as location in the P-d curve.

6 1 CONCLUSION

This paper has showcased the application of a recently evolutionary algorithm based on biology of reproduction of plants/trees towards MPPT in partially shaded PV systems. The new scheme is lucidly explained and computed and measured tracking curves are presented for different shaded PV configurations. MPPT curves with the new strategy is shown to be superior to existing alternatives in terms of convergence speed and reduced duration of PV power ripple during tracking.

NOMENCLATURE

- $I_0$: diode saturation current
- $I_{ph}$: photo current of PV module
- $I_{pv}$: PV module output current
- $I_{sc}$: PV short circuit current
- $P_{pv}$: PV module output power
- $R_s$: Series resistance
- $V_{oc}$: PV open circuit voltage
- $V_{pv}$: PV module output voltage
- $V_t$: thermal voltage
- $C$: value of capacitor
- $d$: duty ratio of the boost converter
- $i_L$: inductor current
- $K$: Boltzmann’s constant
- $k_i$: current temperature coefficient
- $I$: value of inductor
- $R$: value of load resistance
- $r_L$: internal resistance of inductor
- $s$: Laplace operator
- $v_o$: output voltage
- $\Delta T$: change in surface temperature of the panel
- $\eta$: ideality factor
- $\lambda$: solar insolation

REFERENCES

1. Subudhi, B., Pradhan, R.: A comparative study on maximum power point tracking techniques for photovoltaic power systems. IEEE Trans. Sustain. Energy 4(1), 89–98 (2013)
2. Eshram, T., Chapman, P.L.: Comparison of photovoltaic array maximum power point tracking techniques. IEEE Trans. on Energy Conversion 22(2), 439–449 (2007)
3. Wang, Y.J., Hsu, P.C.: Analytical modelling of partial shading and different orientation of photovoltaic modules. IET Renew. Power Gener. 4(3), 272–282 (2010)

4. Patel, H., Agarwal, V.: Maximum power point tracking scheme for PV systems operating under partially shaded conditions. IEEE Trans. Ind. Electron. 55(4), 1689–1698 (2008)

5. Aboudane, H., et al.: Multiple-power-sample based P&O MPPT for fast-changing irradiance conditions for a simple implementation. IET Photovolt. 10(5), 1481–1488 (2020)

6. Yang, Y., Wen, H.: Adaptive perturb and observe maximum power point tracking with current predictive and decoupled power control for grid-connected photovoltaic inverters. J. Mod. Power Syst. Clean Energy 7(2), 422–432 (2019)

7. Kollimala, S.K., Mishra, M.K.: Variable perturbation size adaptive P&O MPPT algorithm for sudden changes in irradiance. IEEE Trans. Sustain. Energy 5(3), 718–728 (2014)

8. Sundareswaran, K., et al.: MPPT of PV systems under partial shaded conditions through a colony of flashing fireflies. IEEE Trans. Energy Conv. 29(2), 463–472 (2014)

9. Badram, A. et al.: Control and circuit technique to mitigate partial shading effects in photovoltaic arrays. IEEE J. Photo-volt. 2(4), 532–546 (2012)

10. Ghasemi, M.A., et al.: MPPT method for PV systems under partially shaded conditions by approximating I–V curve. IEEE Trans. Ind. Electron. 65(5), 3966–3975 (2018)

11. Furtado, A.M.S., et al.: A reduced voltage range global maximum power point tracking algorithm for photovoltaic systems under partial shading conditions. IEEE Trans. Ind. Electron. 65(4), 3252–3262 (2018)

12. Rezk, H., et al.: Design and hardware implementation of a new adaptive fuzzy logic-based MPPT control method for photovoltaic applications. IEEE Access 7, 106427–106438 (2019)

13. Rajendran, S., Srinivasan, H.: Simplified accelerated particle swarm optimization algorithm for efficient maximum power point tracking in partially shaded photovoltaic systems. IET Renew. Power Gener. 10(9), 1340–1347 (2016)

14. Lin, W.-M. et al.: Neural-network-based MPPT control of a stand-alone hybrid power generation system. IEEE Trans. Power Electron. 26(12), 3571–3581 (2011)

15. Rajendran, S., Srinivasan, H.: Simplified accelerated particle swarm optimization algorithm for efficient maximum power point tracking in partially shaded photovoltaic systems. IET Renew. Power Gener. 10(9), 1340–1347 (2016)

16. Sen, T., et al.: Global maximum power point tracking of PV arrays under partial shading conditions using a modified particle velocity-based PSO technique. IET Renew. Power Gener. 12(5), 555–564 (2018)

17. Ishaque, K., et al.: An improved particle swarm optimization (PSO)-based MPPT for PV with reduced steady-state oscillation. IEEE Trans. Power Electron. 27(8), 3627–3638 (2012)

18. Li, H., et al.: An overall distribution particle swarm optimization MPPT algorithm for photovoltaic system under partial shading. IEEE Trans. Ind. Electron. 66(1), 265–275 (2019)

19. Sundareswaran, K., et al.: Enhanced energy output from a PV system under partial shaded conditions through artificial bee colony. IEEE Trans. Sustain. Energy 6(1), 198–209 (2015)

20. Saheesh Krishnan, G., et al.: MPPT in PV systems using ant colony optimisation with dwindling population. IET Renew. Power Gener. 14(7), 1105–1112 (2020)

21. Jiang, L.L., et al.: A novel ant colony optimization-based maximum power point tracking for photovoltaic systems under partially shaded conditions. Energy Build. 58, 227–236 (2013)

22. Nagraha, D.A., et al.: Novel MPPT method based on cuckoo search algorithm and golden section search algorithm for partially shaded PV system. Canadian J. Electr. Comp. Eng. 42(3), 173–182 (2019)

23. Pachaiyan, N., et al.: Novel crowed plant height optimisation algorithm tuned maximum power point tracking for grid integrated solar power conditioning system. IET Renew. Power Gener. 13(12), 2137–2147 (2019)

24. Eltamaly, A.M., et al.: Grade point average assessment for metaheuristic GMPPT techniques of partial shaded PV systems. IET Renew. Power Gener. 13(8), 1215–1231 (2019)

25. Bollipo, R.B., et al.: Critical review on PV MPPT techniques: Classical, intelligent and optimisation. IET Renew. Power Gener. 14(9), 1433–1452 (2020)

26. Polder, A.K., et al.: MPPT methods for solar PV systems: A critical review based on tracking nature. IET Renew. Power Gener. 13(10), 1615–1632 (2019)

27. Josher, M., et al.: A hybrid evolutionary-based MPPT for photovoltaic systems under partial shading conditions. IEEE Access 8, 38481–38492 (2020)

28. Priyadarshi, N., et al.: An experimental estimation of hybrid ANFIS–PSO-based mppt for PV grid integration under fluctuating sun irradiance. IEEE Syst. J. 14(1), 1218–1229 (2020)

29. Padmanaban, S.K., et al.: A hybrid ANFIS-ABC based MPPT controller for PV system with anti-islanding grid protection: Experimental realization. IEEE Access 7, 103377–103389 (2019)

30. Sundareswaran, K., et al.: Development of an improved P&O algorithm assisted through a colony of foraging ants for MPPT in PV system. IEEE Trans. Ind. Inform. 12(1), 187–200 (2016)

31. Ali, A., et al.: Investigation of MPPT techniques under uniform and non-uniform solar irradiation condition—A retrospective. IEEE Access 8, 127368–127392 (2020)

32. Sundareswaran, K., Bhattacharjee, A.: A novel stochastic optimization algorithm inspired from the biology of plant reproduction. In: 2019 IEEE International Conference on Electrical, Computer and Communication Technologies (ICECCT). IEEE, Piscataway (2019)

33. Krishnan, G.S., et al.: Maximum power point tracking in PV systems using plant reproduction algorithm. In: 2020 IEEE International Conference on Power Electronics, Smart Grid and Renewable Energy (PESGRE2020). IEEE, Piscataway (2020)

34. van Dijk, E., et al.: PWM-switch modelling of dc–dc converters. IEEE Trans. Power Electron. 10(6), 659–665 (1995)

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