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An effective maximum power point tracker for partially shaded solar photovoltaic systems

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ABSTRACT

The photovoltaic (PV) systems should operate at a maximum power point (MPP) to extract the maximum possible output power with high tracking efficiency under various operating conditions This paper discusses a new maximum power point tracking (MPPT) technique to extract the peak power from the PV panel/array during partial shaded conditions (PSCs). The proposed algorithm is based on bio-inspired Whale Optimization (WO) with reinitialization process when the PV system is subjected to change in shading pattern, and the algorithm tries to locate the global peak (GP) with a high convergence rate and high tracking efficiency. The proposed algorithm eliminates the computational burden faced by the hybrid MPPT algorithms as discussed in various literature and reduces the power oscillation during the change in operating conditions. The proposed technique is modeled and simulated under different test conditions using MATLAB/Simulink software. The performance of the proposed technique is compared with conventional perturb and observation (PO). Grey Wolf Optimization (GWO) and hybrid GWO (HGWO) techniques in terms of tracking time and tracking efficiency and the simulation result proves that WO technique displays high tracking efficiency (>95%) and less convergence time (<0.15sec) under PSCs with less power oscillations. Moreover, the performance assessment is carried out in terms of mismatching loss, fill factor, and relative power loss/gain.

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1. Introduction

Presently, the renewable energy source has been developed rapidly because it provides clean and green energy. Out of many renewable energy sources, the solar PV plays a vital role to produce the pollution-free energy by converting the solar energy to electrical energy reinforced by MPPT techniques to extract the high output power from the PV panel. The primary objective of locating the MPP is to normalize the operating voltage of the PV module by regulating the output power of the converter. This is possible by changing the converter duty cycle. The duty cycle is adjusted to locate the optimal operating point in the P– V characteristic of the PV module. So, the MPPT control is an important stage in all PV systems (Belhachat and Larbes, 2019; Premkumar et al., 2018; Premkumar and Sowmya, 2019; Riaz et al., 2019; Abdul-Kalaam et al., 2016).

The authors of Haidar et al. (2018), El-Khozondar et al. (2016) and Sutikno et al. (2014) discussed various MPPT methods for the PV systems. The authors of Karami et al. (2017) gave a

* Corresponding author. E-mail address: premkumar.m@gmrit.edu.in (M. Premkumar). detailed review on different MPPT methods such as conventional techniques (incremental conductance (IC) & perturb and observation (PO)), fractional open/short circuit voltage/current methods, and advanced MPPT techniques (based on differential evolution (Kok Soon et al., 2014), artificial neural network (ANN) (Santi Agatino and Giacomo, 2015), particle swarm optimization (PSO) (Yi-Hwa et al., 2012), and fuzzy logic control (FLC) (Ahmad El et al., 2014), etc.). The most familiar MPPT methods are PO and IC, and it has several advantages such as simple structure, low cost, smooth implementation and fewer parameters measurement (Premkumar and Sumithira, 2019). However, these methods fail to locate the MPP under the fast-changing environmental condition. These algorithms settle at a local peak (LP) and result in more power loss.

The limitation of the conventional algorithms are overcome by modern MPPT methods such as grey wolf optimization (GWO) (Mohanty et al., 2016), cuckoo search (Peng et al., 2018), fireflies (Sundareswaran et al., 2014), Jaya algorithm (Huang et al., 2018), differential evolution (Kok Soon et al., 2014), genetic algorithm (Badis et al., 2017), artificial bee colony (Benyoucefa et al., 2015), ANN (Santi Agatino and Giacomo, 2015), and FLC (Ahmad El et al., 2014). These algorithms are classified as metaheuristic algorithms, and it has an advantage that it can be made

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Research paper



effectively to examine the search space (i.e. P-V characteristic) and hence suitable to handle the PSCs. However, it is categorized in term of tracking speed, and these techniques are slower than the conventional counterparts (Ahmed and Salam, 2015; Kermadi and Berkouk, 2017). To improve the convergence rate, the modified soft-computing algorithms are introduced by the researchers. The authors of Ji-Ying et al. (2016) proposed a modified cuckoo search that eliminates the complexity of the conventional cuckoo search technique. Similarly, the hybrid algorithms such as hybrid-GWO (Mohanty et al., 2017), hybrid-WO (Premkumar and Sumithira, 2018), hybrid-FLC (Bahrami et al., 2016), hybrid-ANN (Jiang et al., 2015), hybrid-Jaya (Chao et al., 2019), hybrid-PSO (Farh et al., 2018) etc. are introduced to improve the convergence speed. The author of Mohanty et al. (2017) combines the GWO and PO to achieve high tracking efficiency under a fast and extreme change in solar irradiation. The GWO finds the initial GP, and the PO take cares the final stage to achieve the high convergence rate. The WO and PO is combined to reduce the computation time to realize the improved tracking speed with high tracking efficiency under various operating conditions. The WO finds the initial GP, and the PO takes the final stage to achieve a the high convergence rate (Premkumar and Sumithira, 2018). The ANN is combined with the PO to reach the faster convergence rate, and it was proposed by Jiang et al. (2015). At the initial stage, the ANN locates the GP, and finally, PO locates the peak operating point by controlling the duty cycle of the converter. The Gaussian process regression is combined with Java algorithm is proposed in Chao et al. (2019) for PV array under PSCs. However, the computation burden is more than the standalone MPPT methods.

Based on the issues such as less tracking accuracy, high convergence time, high computation burden, and low tracking efficiency in both the conventional and modern MPPT techniques, this paper proposes a new standalone WO MPPT technique that includes features such as reinitialization which head to its performance improvement. The WO algorithm has more significance compared to various other algorithms due to the exploration and exploitation capability and capable to get rid of the LPs. The search time of the proposed algorithm is reduced by reducing the number of search agents without compromising accuracy. Lower the number of search agents greatly shrinks the convergence time. Moreover, the algorithm climbs to the MPP quickly, while power oscillation is less during the steady-state. In effect, the proposed technique can able to achieve quick and reliable tracking of the GP; guaranteed convergence under partial shading condition, which includes the P-V characteristic with multiple peaks. The paper is organized as follows. Section 2 presents the PV module modeling and the characteristics under partial shading condition, and Section 3 presents the overview of the proposed algorithm and explains how WO algorithm with reinitialization is used for MPPT application. Section 4 discusses the simulation results and further discussions. Section 5 assesses the performance of the proposed MPPT technique in terms of mismatching loss, fill factor, and relative power loss/gain. Lastly, the paper is concluded in Section 6.

2. Solar PV characteristics under various operating conditions

The current (I)-voltage (V) characteristic of the PV panel is non-linear in nature. So, it is necessary to find the optimum operating point to extract maximum output power. However, the output power of the PV module varies when the solar irradiation and the temperature changes. It is necessary to operate the PV panel at MPP, i.e. operation at economic operating region (Madeti and Singh, 2017). The maximum energy is captured from the module when the module resistance is equal to the load resistance. The conventional dc-dc converter is connected between the module and the load to match the load resistance to the internal panel resistance by adjusting the duty ratio of the dc-dc converter.



Fig. 1. Equivalent circuit of the PV module based on the single diode model.

2.1. Mathematical modeling of the solar PV panel

The PV module is modeled as per the single diode model and the equivalent circuit is shown in Fig. 1 (Bellia et al., 2014). The total current of the PV module is presented in Eq. (1).

$$I_{t} = I_{pv}N_{pa} - I_{d}N_{pa} \left(exp\left[\frac{V_{pv} + R_{s}\left(\frac{N_{se}}{N_{pa}}\right)I}{V_{T}aN_{se}}\right] - 1 \right) - \frac{V + R_{s}\frac{N_{se}}{N_{pa}}I}{R_{pa}\left(\frac{N_{se}}{N_{pa}}\right)}$$
(1)

where R_{pa} is shunt resistance, R_s is series resistance, I_d is diodesaturation current, I_{pv} is module current, 'a' is ideality factor, V_{pv} is terminal voltage, and V_T is thermal voltage. The series and parallel connected cells are represented by N_{se} and N_{pa} , respectively. The thermal voltage of the module is presented in Eq. (2).

$$V_{\rm T} = N_{\rm se}kT/q \tag{2}$$

where Boltzmann's constant, k = 1.38×10^{-23} J/K, electron charge, q = 1.6×10^{-19} C, and the junction temperature is represented by T in Kelvin.

The current flow through the PV module is presented in Eq. (3).

$$I_{pv} = \left(I_{pv,N} + K_i \Delta T\right) \frac{G_p}{G}$$
(3)

where the nominal value of the module current is $I_{pv,n}$ at standard test condition (STC), surface irradiation of the PV panel is G_p , G is the solar irradiation at STC, and temperature coefficient is represented by K_i . The expression for saturation of the diode is presented in the Eq. (4).

$$I_{d} = I_{d,N} \left(\frac{T_{N}}{T}\right)^{3} \exp\left[\frac{qE_{g}}{aK} \left(\frac{1}{T_{N}} - \frac{1}{T}\right)\right]$$
(4)

where the nominal reverse saturation current is $I_{d,N}$ and its expression are presented in Eq. (5), the nominal temperature at STC is represented as T_N and E_g is represented for bandgap energy.

$$I_{d,N} = \frac{I_{sc,N}}{\exp\left(\frac{V_{oc,N}}{aV_{T,N}}\right) - 1}$$
(5)

The solar PV module is modeled using MATLAB/Simulink software for the simulation study under different operating condition. This concept can be extended to PV string and PV array. The V– I characteristic and power (P)-voltage (V) characteristic of the PV array under uniform irradiation conditions and PSCs with different patterns are shown in Figs. 2 and 3 respectively.



Fig. 2. PV array characteristics under uniform irradiation condition; (a) P-V characteristic, (b) V-I characteristic.



Fig. 3. PV array characteristics under PSCs; (a) P-V characteristics, (b) V-I characteristics.



Fig. 4. PV array topologies; (a) 2S2P (series-parallel) topology, (b) 4S (series) topology.

2.2. Effects of partial shading condition on solar PV array

The PV array is assembled by grouping the PV modules in parallel and series combinations. If the PV module is subjected to PSCs, it draws more power and develops the heat in junction of the PV cell. As a result, the hot-spot is created, and it can be reduced by connecting the bypass diode across the PV module. Due to presence of the bypass diode, there are multiple peaks present in characteristics of the panel during PSCs, and it is essential to investigate the characteristics of the PV module/string/array under uniform and non-uniform operating conditions (Priti et al., 2017). During partially shaded conditions, the output voltage of the PV cell should meet the criterion which is given in Eq. (6) and



Fig. 5. Bubble-net feed hunting mechanism (Mirjalili and Lewis, 2016).

the bypass diode starts conducting when Eq. (6) is satisfied.

$$V_{pv} = \sum_{k=0}^{m} V_k \ge V_{d,on} \ k \ne 2$$
(6)

where the forward on-state voltage of the diode is represented by V_{d.on}. As discussed earlier, multiple peaks i.e. multiple LPs and single GP under PSCs are existed due to the conduction of the bypass diode. The output current of the module depends on the solar irradiation and is directly proportional. As a result, the solar irradiation decides the short circuit current of the PV module. Similarly, the output voltage of the PV module depends on the cell temperature and is inversely proportional. However, increase in temperature also increases the PV output current. So, decrease in output voltage due to high cell temperature results in low PV output power. Fig. 4 shows the solar PV array configurations such as four series-connected modules (4S) and two series-connected string with two parallel paths (2S2P). It is observed from Fig. 4 that, the PV array is provided with bypass diodes across each panel and one blocking diode to protect the array from the reverse current.

Since the temperature and the solar insolation are varying continuously all over the day, the optimal operating point of the PV module is varying continuously. The power loss can be high if the operating point is not close to the MPP. Therefore, it is essential to find the MPP, and it can be achieved by employing a suitable MPPT technique.



Fig. 6. Flowchart of the proposed WO MPPT technique with reinitialization process.



Fig. 7. Block diagram of the solar PV system with WO MPPT technique.

3. Overview of the proposed WO MPPT method with reinitialization

3.1. Basic concepts of whale optimization algorithm

The whale optimization algorithm is one of the smart bioinspired algorithms, and it is motivated by hunting actions of the whale. The humpback whales are much superior in hunting, and this behavior can be used to solve the non-linear problems in engineering. The name of the hunting, mechanism is based on bubble-net feed and the same has been displayed in Fig. 5 (Mirjalili and Lewis, 2016). These whales hunt the small fishes nearby the surface. The hunting starts with the bubbles in the spherical path and proceeds to encircle the target, bubble-net feed and the search the targets in exploration and exploitation search spaces. The search agent finds the target position and surrounds the target.

Due to unknown initial search-space position, the algorithm assumes the target as the current best solution, and the algorithm locates the best whale while other attempts to update its position. The agents swim toward the target prey within the shrinking circle and update the best position. The modeling of hunting action of the whale is as follows:

$$\begin{aligned} \overrightarrow{C} &= \left| \overrightarrow{B} \cdot \overrightarrow{Y_{n}}^{*}(m) - \overrightarrow{Y_{n}}(m) \right| \end{aligned} (7) \\ \overrightarrow{Y_{n}}(m+1) \\ &= \left\{ \overrightarrow{Y_{n}}^{*}(m) - \overrightarrow{A} \cdot \overrightarrow{C} & \text{if } k < 0.5 \text{ (exploration)} \\ \overrightarrow{Q}^{*} \cdot e^{bi} \cos\left(2\pi b\right) + \overrightarrow{Y_{n}}^{*}(m) & \text{if } k > 0.5 \text{ (exploitation)} \right\} \end{aligned} (8)$$

where the number of iteration is represented by m, \overrightarrow{C} , \overrightarrow{A} and \overrightarrow{B} are the vector coefficients, $\overrightarrow{Y_n}$ is search agents position vector, and $\overrightarrow{Y_n}^*$ is a vector position for the current best and the same has been updated when a better solution has arrived after each iteration. $\overrightarrow{C}^* = |\overrightarrow{Y_n}^*(m) - \overrightarrow{Y_n}(m)|$, indicates the spiral path shape and distance, b is a random number, [-1,1], and n is a random number, [0,1]. If k < 0.5, shrinking-encircling hunting is selected, else spiral hunting is selected. The vectors coefficients such as \overrightarrow{A} and \overrightarrow{B} are computed in Eqs. (9)–(10).

$$\vec{A} = 2 \vec{q} \cdot \vec{r_1} - \vec{q}$$
(9)
$$\vec{B} = 2 \vec{r_2}$$
(10)

where the random vectors $\overrightarrow{r_1}$ and $\overrightarrow{r_2}$ are [0,1] and \overrightarrow{q} decreases from 2 to 0 over the iteration in the search spaces.

3.2. Implementation of WO MPPT technique

During various operating conditions such as uniform and nonuniform irradiation, the proposed WO MPPT technique tries to locate the GP with less power oscillation and high tracking efficiency. In this paper, WO is applied as a direct control MPPT method, i.e., controlling the duty cycle by assuming the position of the updated search agent as a duty cycle to reduce the power oscillation. This direct control method reduces power loss and hence improves efficiency. When search agents are closer to each other, the best agent's position is updated. The flowchart of the proposed MPPT technique is shown in Fig. 6 and the procedure for the implementation is described as follows.

Step 1 – Search agent position is initialized within 20% (d_{min}) - 92% (d_{max}) of the conventional dc–dc converter duty cycle.

Step 2 — The converter is activated at each best position of the search agent to increase the PV array output power and recalculate the power by computing the PV voltage and current at each duty cycle.

Step 3 – Position of the search agent, i.e. duty cycle of the converter is adjusted as per the objective function to maximize the output is given in Eq. (11).

$$P(d_s^m) > P(d_s^{m-1}) \tag{11}$$

Where the PV array output power is represented by P, the duty cycle of the converter is d, the number of search agent is 's' and the number of iteration is 'm'. The duty cycle of the converter is derived from Eq. (8) and expressed in Eq. (12) with the initial assumption of k < 0.5.

$$d_{s}(m+1) = d_{s}(m) - \overrightarrow{A} \cdot \overrightarrow{C}$$
(12)

Step 4 – Steps 3–4 are repeated until the convergence/termination criteria met by all the search agents. The termination criterion is presented in Eq. (13).

$$\frac{P^m - P^{m-1}}{P^m} \ge 0.1$$
 (13)

The proposed WO algorithm is reinitialized by computing the change in output power using Eq. (13). The WO algorithm is reinitialized when the PV system is subjected to the change in shading pattern. This reinitialization process makes the PV system to track the GP accurately. The algorithm locates the GP with a small step size to reduce the power oscillation and offers high tracking efficiency. According to the above discussions, the pseudo-code of WO algorithm is as follows and various parameters of different algorithms are listed in Table 1.

The experimental setting is very important to get the optimal value. For example, random numbers are selected to balance the

Pseudo Code - Start procedure
Initialize s, d _{min} , d _{max} , Max_iter, objective function, dim (number of objective function)
Calculate the fitness $(P(d_s^m))$ of each search agent
D_s = the best search agent
while (m < Max_iter)
for each search agent (s) find the fitness do
$fitness(s) = V_{pv}(s) * I_{pv}(s)$
Update leader by comparing the fitness at each search agent and old leader score
end for
for each search agent (s) do
update the parameters such as q, A, p, B
if $(k < 0.5)$
if(U < 1)
update search agent by Eq. 12
elseif ($ \mathbf{U} \ge 1$)
Select a random search agent
Update search agent by Eq. 12
end if
elseif (k \ge 0.5)
Update the position of current search agent Eq. 8
end if
end for
m=m+1
end while
return D _k end procedure

Various parameters of algorithms for the simulation study.

S. No.	Parameters	WO	GWO	HGWO
1.	Initial population	Randomly between 0 and 1	Randomly between 0 and 1	Randomly between 0 and 1
2	Number of iteration, m	100	140	160
3	Number of search agents, s	12	12	12
4	Termination criteria	Max_iter	Max_iter	Max_iter
5	p, the random number which decides the	[1,0]	NA	NA
	exploration and exploitation phase			
6	Sampling time	5e-5	5e-5	5e-5
7	d_old (Initial duty cycle to start the process)	0.3	0.3	0.3

exploitation and exploration phase of the search agent which improves the chance of getting the GP. There are several studies discussed the selection of optimal value (Ahmed and Salam, 2015; Kermadi and Berkouk, 2017). There are series of experiments done to get the possible output from the algorithm. Since this paper dealt with one-dimensional function (single objective function), the selection of parameters is straight forward. The search agents are limited by balancing the computation time and the convergence accuracy. The parameters are selected based on the discussions from Ahmed and Salam (2015) and Kermadi and Berkouk (2017) for the simulation study in this paper.

The duty cycle of the dc–dc converter is provided by the vector position of the best search agent to eliminate the use of the PID controller. The block diagram of the solar PV system with the proposed MPPT technique is shown in Fig. 7. Depending on various shading patterns, the output power of the PV module/array keeps varying. As discussed above, the algorithm is reinitialized by assessing the power oscillation. Tracking accuracy is increased by selecting a high number of search agents, however, the computation complexity and tracking time is increased. In this paper, the input variable is varied with other parameters constant and the effect on the objective function is observed. The WO algorithm attempts to find a global optimum solution by achieving the best position in both the search spaces. After thorough study and many trials running, the parameters are selected. So, 12 search agents are selected in this paper to reduce the computation complexity without compromising the accuracy.



Fig. 8. P-V characteristic of the PV array under STCs.

4. Simulation results and discussions

The proposed algorithm is modeled using MATLAB/Simulink software, and the simulation was carried out on the PV system under different test cases such as STC, PSCs, rapid and extreme change in insolation. The individual PV module parameters are



Fig. 9. Simulation waveforms at STCs; (a) PV array output power, (b) PV array output voltage, (c) PV array output current, (d) Duty cycle.

as follows: Make: Andslite Solar Panel, $P_{mpp} = 10.16$ W, $V_{mpp} = 17.83$ V, $I_{mpp} = 0.57$ A, $V_{oc} = 21.75$ V, $I_{sc} = 0.61$ A. The specifications of the boost converter are as follows: input voltage range (V_{in}) is 40–100 V, output voltage range (V_{out}) is 120–300 V, inductance (L_{dc}) is 4.17 mH, input capacitor (C_{in}) is 220 μ F, output capacitor (C_o) is 220 μ F, switching frequency (F_{sw}) is 20 kHz, and

maximum power (P_{max}) is 100 W. The 4S PV array configuration is selected to validate the performance of the proposed technique. The other array configurations such as series-parallel, total crosstied, bridge-link, and honey-comb are not considered in this paper. However, the proposed technique can be well-suited for other PV array topologies also.



Fig. 10. Different shading patterns created for case-I.

4.1. Test Case-I: STCs

At first, the performance of the proposed technique was carried out under STCs. The STC is an industry standard which specifies the PV module performance with cell temperature at 25 °C, the solar irradiance at 1000 W/m² and air mass at 1.5 spectrums. However, the conditions for STC are hardly met in real-time. Fig. 8 shows the PV array characteristic (P–V) and Fig. 9 shows various output parameters such as PV array output voltage, output current, output power, and duty cycle under STCs.

As shown in Fig. 9(a), the WO MPPT technique can able to track the MPP of the array i.e. 40.53 W out of 40.65 W at STCs. The performance of the WO technique is confirmed by comparing the results by the conventional PO algorithm, GWO and HGWO algorithm. The PO algorithm can able to track 40.52 W, GWO algorithm can able to track 40.51 W and HGWO algorithm can able to track 40.53 W. It is observed that there is a small oscillation exists in PO method and it can be reduced by selecting smaller step size, however, it will further increase the convergence time. The tracking time of WO, PO, GWO and HGWO is 0.1246 s, 0.1515 s, 0.1248 s, and 0.1285 s, respectively. All the algorithms can able to track almost same MPP under STCs with different tracking time. It is concluded that the conventional PO algorithm and modern MPPT techniques such as WO, GWO and HGWO performing better in STCs and exhibits almost similar characteristics. Fig. 9(b)-(c) shows the PV array output voltage and current are supporting waveforms which verifies the performance of the PV system. Fig. 9(d) shows the duty cycle adjustment under STCs. It is observed that the optimal duty cycle of WO, PO, GWO and HGWO is 0.3263, 0.4485, 0.3263 and 0.3111, respectively at the initial stage of the algorithms.

4.2. Test Case-II: PSCs

The PV system with the proposed WO MPPT technique is validated under PSCs to locate the GP instead of the LPs. The shading patterns are created on the solar PV array as shown in Fig. 10. The P–V characteristic of 4S PV array configuration under PSCs (for two different shading patterns) is shown in Fig. 11. As shown in Fig. 11, the P–V characteristic has three LPs and one GP under both pattern-I and pattern-II. The local peaks are due to the by-pass diode. The primary duty of the converter is duty cycle adjustment to achieve the maximum power condition under PSCs, and it can be varied based on the PV array output voltage and PV array output current. During the search duration of MPP, the PO algorithm tries to settle at third local peak due to the fixed step size and fails to reach the GP.



Fig. 11. P-V characteristic of the PV array under PSCs.

As shown in Fig. 10, there are two shading patterns created at 0.25 s interval to validate the algorithm. As shown in Fig. 11, the P–V characteristic at pattern-I has multiple LPs such as LP1 at 7.8 W, LP2 at 14.58 W, LP3 at 13.22 W, and one GP at 16.5 W and the P–V characteristic at pattern-II has multiple LPs such as LP1 at 8.2 W, LP2 at 17.38 W, LP3 at 26.66 W, and one GP at 31.84 W. The PV system is simulated, and various waveforms are shown in Fig. 12.

As shown in Fig. 12(a), the pattern-I is created at t = 0, and pattern-II is created at t = 0.25 s The PV system with the WO algorithm can able to track the maximum power of 15.97 W at t = 0.1297 s under pattern-I. The performance of the WO algorithm is validated by comparing the test results given by the conventional PO algorithm, GWO, and HGWO algorithm. The PO algorithm can able to track 13.12 W, GWO algorithm can able to track 14.26 W and HGWO algorithm can able to track 14.88 W. The tracking time of PO, GWO and HGWO is 0.1620 s, 0.1537 s, and 0.1328 s respectively. The PV system with the WO algorithm can able to track the maximum power of 30.41 W at t = 0.1849 s under pattern-II. The PO algorithm can able to track 23.13 W, GWO algorithm can able to track 28.38 W and HGWO algorithm can able to track 29.12 W. The tracking time of PO, GWO, and HGWO is 0.2147 s, 0.1957 s, and 0.1798 s respectively. Fig. 12(b)–(c) shows the PV array output voltage and current are supporting waveforms which verifies the performance of the PV system. Fig. 12(d) shows the duty cycle adjustment under PSCs. It is observed that the optimal duty cycle of WO, PO, GWO, and HGWO is 0.2639, 0.4485, 0.3165, and 0.2445, respectively at the



Fig. 12. Simulation waveforms at PSCs; (a) PV array output power, (b) PV array output voltage, (c) PV array output current, (d) Duty cycle.

initial stage of the algorithms. It is observed that the conventional PO algorithm tries to track the GP under PSCs and the convergence time is higher than the proposed WO algorithm. The other algorithms such as GWO and HGWO does not have any special operator to set apart certain iteration to the exploitation or the exploration search space because it updates the search agent's position in one format, so the probability of falling into LP is more likely increased in these algorithms. Due to the hybridization, the HGWO can able to track the maximum power almost comparable to the WO algorithm due to the guidance of the PO near the GP. It



Fig. 13. Different shading patterns created for case-III.



Fig. 14. P-V characteristic of the PV array under a rapid change in insolation.

is concluded that the WO algorithm tries to settle very nearer to the GP because the whales are updated, and reinitialized in both phases independently to improve the convergence accuracy.

4.3. Test Case-III: Rapid change in solar irradiation

The PV system with the proposed WO MPPT technique is validated under a rapid change in insolation to locate the GP instead of the LPs. The shading patterns are created on the solar PV array as shown in Fig. 13. The P–V characteristic of the PV array under a rapid change in insolation (for three shading patterns) is shown in Fig. 14.

As shown in Fig. 13, there are three different shading patterns are created at 0.2 s interval to validate the algorithm, and the respective P–V characteristic is shown in Fig. 14. As shown in Fig. 14, the P–V characteristic has one GP under shade-I at 38.36 W, shade-II at 33.64 W and shade-III at 26.47 W. The PV system is simulated, and various waveforms are shown in Fig. 15.

As shown in Fig. 15(a), the shade-I is created at t = 0, shade-II is created at t = 0.2 s and the shade-III is created at t = 0.4 s The PV system with the WO algorithm can able to track the maximum power of 37.06 W at t = 0.115 s under shade-I. The performance of the WO algorithm is validated by comparing the test results given by the conventional PO algorithm, GWO, and HGWO algorithm. The PO algorithm can able to track 32.68 W, GWO algorithm can able to track 36.65 W. The tracking time of PO, GWO and HGWO is 0.189 s, 0.1459 s, and 0.1759 respectively. The PV system with the WO algorithm can able to track the maximum power of 31.34 W at t = 0.0720 s under shade-II. The PO, GWO and HGWO can able

to track 27.87 W, 30.42 W, and 31.12 W respectively at 0.1698 s, 0.1178 s, and 0.1028 s respectively under shade-II. The PV system with WO algorithm can able to track the maximum power of 24.71 W at t = 0.0850 s under shade-III. The PO, GWO and HGWO can able to track 20.04 W, 22.14 W, and 23.86 W respectively at 0.1598 s. 0.1278 s. and 0.1141 s respectively under shade-III. Fig. 15(b)-(c) shows the PV array output voltage and current are supporting waveforms, which verifies the performance of the PV system. Fig. 15(d) shows the duty cycle adjustment under raid change in insolation condition. It is observed that the optimal duty cycle of WO, PO, GWO, and HGWO is 0.2185, 0.4485, 0.3165, and 0.2082, respectively at the initial stage of the algorithms. It is also observed that the conventional PO algorithm tries to track the GP (but fails to settle at GP) under rapid change in insolation conditions, and the convergence time is higher than the proposed WO algorithm and other algorithms such as GWO and HGWO. As discussed earlier, the GWO and HGWO is not having any special operator, the probability of falling into LP is more likely increased. Due to the hybridization, the HGWO can able to track the maximum power almost comparable to the WO algorithm due to the guidance of the PO near the GP. It is concluded that the WO algorithm tries to settle very nearer to the GP because the whales are updated and reinitialized in both phases independently to improve the convergence accuracy.

4.4. Test Case-IV: Extreme change in solar irradiation

The PV system with the proposed WO MPPT technique is validated under the extreme change in insolation to locate the GP instead of the LPs. The shading patterns are created on the solar PV array as shown in Fig. 16. The P–V characteristic of the PV array under the extreme change in insolation conditions is shown in Fig. 17.

As shown in Fig. 16, there are four different shading patterns created at 0.15 s interval (except shade-VI and shade-VII) to validate the algorithm, and the respective P–V characteristic is shown in Fig. 17. As shown in Fig. 17, the P–V characteristic has one GP under shade-IV at 40.65 W, shade-V at 20.49 W and shade-VI at 8.051 W. The GP at shade-IV and shade-VII is The PV system is simulated, and various waveforms are shown in Fig. 18.

As shown in Fig. 18(a), the shade-IV is created at t = 0, shade-V is created at t = 0.15 s, shade-VI is created at 0.3 s and the shade-VII is created at t = 0.5 s The PV system with the WO algorithm can able to track the maximum power of 40.53 W at t = 0.1246 s under shade-IV. The PO algorithm can able to track 40.52 W, GWO algorithm can able to track 40.53 W. The tracking time of WO, PO, GWO and HGWO is 0.1246 s, 0.1515 s, 0.1248 s, and 0.1285 s respectively.



Fig. 15. Simulation waveforms at the rapid change in insolation; (a) PV array output power, (b) PV array output voltage, (c) PV array output current, (d) Duty cycle.

All the algorithms can able to track almost the same MPP under STCs with different tracking time. The PV system with the WO algorithm can able to track the maximum power of 16.41 W at

t=0.1209 s under shade-V. The PO, GWO and HGWO can able to track 11.87 W, 14.69 W and 15.24 W respectively at 0.1462 s, 0.1411 s, and 0.1396 s respectively under shade-V. The PV system



Fig. 16. Different shading patterns created for case-IV.



Fig. 17. P-V characteristic of the PV array under the extreme change in insolation.

with the WO algorithm can able to track the maximum power of 7.28 W at t = 0.1132 s under shade-VI. The PO, GWO, and HGWO can able to track 4.96 W, 6.11 W, and 7.91 W, respectively at 0.1478 s, 0.1411 s, and 0.1359 s, respectively under shade-VI. The maximum power extraction at shade-VII is similar to shade-IV with the different tracking time. The tracking time of various algorithms such as WO, PO, GWO, and HGWO is 0.1246 s, 0.1549 s, 0.1252 s, and 0.1292 s, respectively under shade-VII. Fig. 18(b)–(c) shows the PV array output voltage and current are supporting waveforms which verifies the performance of the PV system. Fig. 18(d) shows the duty cycle adjustment under raid change in insolation condition. It is observed that the optimal duty cycle of WO, PO, GWO, and HGWO is 0.3111, 0.4485, 0.3111, and 0.3263, respectively at the initial stage of the algorithms. It is also observed that the conventional PO, GWO and HGWO MPPT techniques tries to track the GP (but fails to settle at GP) under the extreme change in insolation conditions and the convergence time is higher than the proposed WO algorithm. It is observed that there is a small oscillation exists in the PO method, and it can be reduced by selecting smaller step size however, it will further increase the convergence time. As discussed earlier, the GWO and HGWO are not having any special operator, the probability of falling into LP is more likely increased. Due to the hybridization, the HGWO can able to track the maximum power almost comparable to the WO algorithm due to the guidance of the PO near the GP. It is concluded that the WO algorithm tries to settle very nearer to the GP because the whales are updated, and reinitialized in both phases independently to improve the convergence accuracy.

5. Performance assessment of various MPPT techniques under PSCs

This section of the paper discusses the evaluation parameters of different MPPT techniques such as PO, GWO, HGWO, and proposed WO algorithm under PSCs to select the better MPPT technique that delivers high operating performance. Firstly, the performance comparison is made with respect to tracking efficiency and convergence rate for the 4S PV array configurations with the various shading patterns. The comparison details in terms of tracking time and tracking efficiency is presented in Table 2.

Figs. 19–20 displays the graphical relationship between different MPPT techniques such as WO, PO, GWO, and HGWO. The proposed WO MPPT technique is assessed with the conventional algorithms such as PO, GWO, and HGWO for real-world applications. As per the previous discussions and Figs. 8–18, it is witnessed that the WO technique finds the GP accurately under various shading patterns. In addition, the WO based MPPT technique results in a high convergence rate and high MPPT tracking efficiency.

The performance assessment is carried out by calculating the theoretical power generations under different shading conditions, fill factor (FF), relative power loss (RPL), relative power gain (RPG), and mismatching loss (ML). The ML is calculated in percentage and represented as ΔP_L and it is given in Eq. (14).

$$\Delta P_{L} = \frac{P_{mpp} - P_{PSC}}{P_{mpp}} * 100$$
⁽¹⁴⁾

where P_{mpp} is maximum power generation under uniform irradiance condition, and P_{PSC} is power generation at certain PSC. P_{PSC} is nothing but GP at the respective PSC. Another important assessment parameter is FF, and it can be calculated using Eq. (15). If the value of FF is near to unity then the performance of the solar PV system is greater.

$$FF = \frac{GP \text{ at respective PSC}}{V_{oc} * I_{sc}}$$
(15)

The performance comparison between various MPPT techniques under different patterns in terms of ML and FF is presented in Table 3. Since S-IV and S-VII shading patterns are similar, the S-VII pattern is not considered for performance assessment comparison.

The theoretical power generation (P_{th}) can be calculated by using Eq. (16). Where G_p is solar irradiance under PSC of the individual module, G is solar irradiance under STC, and the total



Fig. 18. Simulation waveforms at the extreme change in insolation; (a) PV array output power, (b) PV array output voltage, (c) PV array output current, (d) Duty cycle.

number of PV modules is represented as 'j'.

$$P_{th} = \sum_{j=1}^{j=4} \left[\frac{G_p}{G} * P_{mpp,j} \right]$$
(16)

Theoretical power generation can be useful for calculating the relative power loss of the respective MPPT technique. The relative power loss (RPL) of the MPPT technique can be calculated by

Performance comparison of WO, PO and IC MPPT methods.

Shading conditions		MPPT	PV power (W)	Tracking time (s)	P _{max} (W)	$\eta_{ m tracking}$ (%)
STC		WO PO GWO HGWO	40.53 40.52 40.51 40.53	0.1246 0.1515 0.1248 0.1285	40.65	99.70 99.68 99.66 99.70
PSC	Pattern-I (P-I)	WO PO GWO HGWO	30.41 23.13 28.38 29.12	0.1849 0.2147 0.1957 0.1798	31.84	95.51 72.64 89.13 91.46
	Pattern-II (P-II)	WO PO GWO HGWO	15.97 13.12 14.26 14.88	0.1297 0.1620 0.1537 0.1328	16.58	96.32 79.13 86.01 89.75
	Shade-I (S-I)	WO PO GWO HGWO	37.06 32.68 35.12 36.65	0.115 0.1890 0.1459 0.1759	38.36	96.61 85.19 91.55 95.54
Rapid change in insolation	Shade-II (S-II)	WO PO GWO HGWO	31.34 27.87 30.42 31.12	0.0720 0.1698 0.1178 0.1028	33.64	93.16 82.85 90.43 92.51
	Shade-III (S-III)	WO PO GWO HGWO	24.71 20.04 22.14 23.86	0.0850 0.1598 0.1278 0.1141	26.47	93.35 75.71 83.64 90.14
	Shade-IV (S-IV)	WO PO GWO HGWO	40.53 40.52 40.51 40.53	0.1246 0.1515 0.1248 0.1285	40.65	99.70 99.68 99.66 99.70
Extreme change in insolation	Shade-V (S-V)	WO PO GWO HGWO	16.41 11.87 14.69 15.24	0.1209 0.1462 0.1411 0.1396	20.49	80.09 57.93 71.69 74.38
	Shade-VI (S-VI)	WO PO GWO HGWO	7.28 4.96 6.11 7.91	0.1132 0.1478 0.1411 0.1359	8.051	90.42 61.61 75.89 98.25
	Shade-VII (S-VII)	WO PO GWO HGWO	40.55 40.52 40.51 40.54	0.1246 0.1549 0.1252 0.1292	40.65	99.75 99.68 99.66 99.73







Fig. 20. Tracking efficiency of various MPPT techniques.

Table 3

Performance assessment comparison among various MPPT techniques.

MPPT	P-I		P-II	-	S-I	-	S-II		S-III		S-IV		S-V		S-VI	
	ML (%)	FF														
WO	25.2	0.75	60.7	0.39	8.83	0.91	22.9	0.77	39.2	0.61	0.3	0.99	59.6	0.40	82	0.18
PO	43.1	0.57	67.7	0.32	19.6	0.80	31.4	0.69	50.7	0.49	0.32	0.99	70.7	0.29	87.7	0.12
GWO	30.2	0.7	64.9	0.35	13.6	0.86	25.2	0.75	45.5	0.54	0.34	0.99	63.9	0.36	85	0.15
HGWO	28.4	0.72	63.4	0.37	9.84	0.90	23.4	0.77	41.3	0.59	0.3	0.99	62.5	0.37	80.5	0.19

using Eq. (17). The relative power gain (RPG) with respect to the maximum output power of the PO technique can be calculated by using Eq. (18).

$$RPL = P_{th} - P_{mpp} at GP$$
(17)

$$RPG = \frac{P_{mpp,i} - P_{mpp, PO}}{P_{mpp, PO}} * 100$$
(18)

where 'i' represents various MPPT techniques such as WO, GWO and HGWO, and $P_{mpp,PO}$ represents the output power of the PO technique. For the benefit of readers, the comparison between various MPPT techniques such as WO, PO, GWO, and HGWO based on the RPL and RPG is discussed in this paper. The performance comparison is presented in Tables 4–5.

Fig. 21 shows the maximum output power delivered by various MPPT techniques under various shading patterns. Figs. 22–23 shows the performance comparison in terms of RPL and RPG among various MPPT techniques under different shading patterns. The data label for WO and HGWO techniques are highlighted in Figs. 20–22 for the better comparison. Since S-IV and S-VII shading patterns are similar, the S-VII pattern is not considered for graphical comparison.

The result acquired from the simulation describes the relationship between the output power and MPPT technique within the PV systems. From Table 4 and Fig. 22, the PV MPPT techniques are ordered in terms of RPL as follows: PO > GWO > HGWO > WO, and from Table 5 and Fig. 23, the PV MPPT techniques are ordered in terms of RPG as follows: PO < GWO < HGWO < WO. Moreover, the simulation results concluded that the WO MPPT technique is superior to other MPPT techniques such as PO, GWO and HGWO with less power loss and high power gain. In addition, the proposed technique is performing better than the PO, GWO and HGWO in terms of tracking time, ML, FF and tracking efficiency. To conclude, the WO MPPT technique with reinitialization is capable of flexible toward different operating conditions such as STC, PSCs, rapid insolation change, and extreme insolation change. The various features of the proposed MPPT technique and other techniques are presented in Table 6.

6. Conclusions

This paper discussed a new MPPT technique based on the WO algorithm with reinitialization to track the GP when the PV module is subjected to different shading patterns such as P-I, P-II, and S-I to S-VII. This paper has assessed the performance of the WO algorithm and other algorithms that affect the power generation. The mathematical modeling of the WO algorithm is carried out and the implementation of the WO algorithm for MPPT application is explained in detail. The computer simulation was carried out to validate the performance of the proposed technique. The proposed technique is validated with 4S PV array configurations under different shading conditions such as STCs, PSCs, rapid insolation change, and extreme change in insolation. The performance of the MPPT techniques is assessed based on the parameters such as maximum power extraction, tracking time, tracking efficiency, ML, FF, RPG, and RPL. From the detailed simulation and discussions, it is concluded that the proposed technique is superior in tracking with less time, less power loss and high efficiency. The computation burden of the WO algorithm is reduced by selecting 12 search agents with 100 iterations for the simulation analysis. Finally, the proposed MPPT technique has less standard deviation which allows locating the GP effectively and accurately. The following are the major contribution of this paper: (i) modeling and implementation of a new MPPT application to track the GP with less power oscillation, less tracking time

RPL comparison of various MPPT techniques.

MPPT	PT P-I $P_{th} = 34.55 W$		P-I $P-IIP_{th} = 34.55 \text{ W} P_{th} = 24.39 \text{ W}$		$\begin{array}{ccc} S-I & S-II \\ P_{th} = 39.13 \text{ W} & P_{th} = 34.05 \text{ W} \end{array}$		S-III $P_{th} = 29.27 \text{ W}$		S-IV $P_{th} = 40.65$ W		S-V $P_{th} = 20.49$ W		S-VI $P_{th} = 8.13$ W			
	P _{mpp} (W)	RPL (W)	P _{mpp} (W)	RPL (W)	P _{mpp} (W)	RPL (W)	P _{mpp} (W)	RPL (W)	P _{mpp} (W)	RPL (W)	P _{mpp} (W)	RPL (W)	P _{mpp} (W)	RPL (W)	P _{mpp} (W)	RPL (W)
WO	30.41	4.14	15.97	8.42	37.06	2.07	31.34	2.71	24.71	4.56	40.53	0.12	16.41	4.08	7.28	0.85
PO	23.13	11.42	13.12	11.27	32.68	6.45	27.87	6.18	20.04	9.23	40.52	0.13	11.87	8.62	4.96	3.17
GWO	28.38	6.17	14.26	10.13	35.12	4.01	30.42	3.63	22.14	7.13	40.51	0.14	14.69	5.8	6.11	2.02
HGWO	29.12	5.43	14.88	9.51	36.65	2.48	31.12	2.93	23.86	5.41	40.53	0.12	15.24	5.25	7.91	0.22

Bold values point toward the best performance of MPPT technique.

Table 5

RPG comparison of various MPPT techniques.

MPPT	MPPT P-I		P-II		S-I	S-I		S-II		S-III		S-IV		S-V		
	P _{mpp} (W)	RPG (%)	P _{mpp} (W)	RPG (%)	P _{mpp} (W)	RPG (%)	P _{mpp} (W)	RPG (%)	P _{mpp} (W)	RPG (%)	P _{mpp} (W)	RPG (%)	P _{mpp} (W)	RPG (%)	P _{mpp} (W)	RPG (%)
WO	30.41	31.5	15.97	21.7	37.06	13.4	31.34	12.5	24.71	23.3	40.53	0.0	16.41	38.2	7.28	46.8
PO	23.13	0.0	13.12	0.0	32.68	0.0	27.87	0.0	20.04	0.0	40.52	0.0	11.87	0.0	4.96	0.0
GWO HGWO	28.38 29.12	22.7 25.9	14.26 14.88	8.7 13.4	35.12 36.65	7.5 12.1	30.42 31.12	9.1 11.7	22.14 23.86	10.5 19.1	40.51 40.53	0.0 0.0	14.69 15.24	23.8 28.4	6.11 7.91	23.2 59.5

Bold values point toward the best performance of MPPT technique.



Fig. 21. Maximum output power generation under shading conditions.



Fig. 22. Comparison between various MPPT techniques in terms of RPL.

and high efficiency, (ii) simulation experiments are carried out under different test cases to test the efficiency of WO algorithm with the other methods, (iii) performance assessment was carried out in terms of ML, FF, RPG, and RPL. Based on these discussions, the descending order of the MPPT technique is WO, HGWO, GWO, and PO technique. The present work can be extended by tracking



Fig. 23. Comparison between various MPPT techniques in terms of RPG with respect PO.

Features of various MPPT techniques.

MPPT techniques	Regular tuning	Response	Power oscillation	GMPP convergence	Complexity
WO	No	Quick & accurate	Less	Guaranteed	Medium
PO	Yes	Sluggish & less accuracy	High	Not guaranteed	Easy
GWO	No	Moderate & less accurate	Less	Guaranteed	Medium
HGWO	No	Quick & accurate	Less	Guaranteed	High

more input parameters that depend on time and operating conditions. Further, the work in this paper that has been carried out to the boost converter is restricted by considering high switching frequency.

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References

- Abdul-Kalaam, R., Muyeen, S., Al-Durra, A., 2016. Review of maximum power point tracking techniques for photovoltaic system. Glob. J. Control Eng. Technol. 6 (2), 8–18.
- Ahmad El, K., Nasrudin, A.R., Jeyraj, S., Nasir Uddin, M., 2014. Fuzzy logic controller based SEPIC converter for maximum power point tracking. IEEE Trans. Ind. Appl. 50 (4), 2349–2358.
- Ahmed, J., Salam, Z., 2015. A critical evaluation on maximum power point tracking methods for partial shading in PV systems. Renew. Sustain. Energy Rev. 47, 933–953.
- Badis, A., Mansouri, M.N., Boujmil, M.H., 2017. A genetic algorithm optimized MPPT controller for a PV system with DC-DC boost converter. In: Proc. of International Conference on Engineering &, Monastir, pp. 1-6.
- Bahrami, M., Zandi, M., Gavagsaz, R., Nahid-Mobarakeh, B., Pierfederici, S., 2016. A new hybrid method of MPPT for photovoltaic systems based on FLC and three point-weight methods. In: Proc. of 7th Power Electronics and Drive Systems Technologies Conference, Tehran, pp. 446-450.
- Belhachat, F., Larbes, C., 2019. Comprehensive review on global maximum power point tracking techniques for PV systems subjected to partial shading conditions. Sol. Energy 183, 476–500.
- Bellia, H., Youcef, R., Fatima, M., 2014. A detailed modeling of photovoltaic module using MATLAB. NRIAG J. Astron. Geophys. 3 (1), 53–61.
- Benyoucefa, A.S., Chouderb, A., Karaa, K., Silvestrec, S., Sahedaa, O.A., 2015. Artificial bee colony based algorithm for maximum power point tracking (MPPT) for PV systems operating under partial shaded conditions. Appl. Soft Comput. 32, 38–48.
- Chao, H.u., Long, W., Huan, L., Xiong, L., Jenq-Haur, W., 2019. A hybrid global maximum power point tracking method for photovoltaic arrays under partial shading conditions. Optik Int. J. Light Electron Opt. 180, 665–674.

- El-Khozondar, Hala J., El-Khozondar, Rifa J., Matter, Khaled, Suntio, Teuvo, 2016. A review study of photovoltaic array maximum power tracking algorithms. Renewables 3 (3), 1–8.
- Farh, Hassan M.H., Eltamaly, Ali M., Othman, Mohd F., 2018. Hybrid PSO-FLC for dynamic global peak extraction of the partially shaded photovoltaic system. PLoS One 13 (11), e0206171-1-16.
- Haidar, I., Mekhilef, S., Mohamed Shah, N.B., Soon, T.K., Seyedmah mousian, M., Horan, B., Stojcevski, A., 2018. Performance evaluation of maximum power point tracking approaches and photovoltaic systems. Energies 11, 365–1–24.
- Huang, C., Wang, L., Yeung, R.S.C., Zhang, Z., Chung, H.S.H., A., Bensoussan., 2018. A prediction model-guided jaya algorithm for the PV system maximum power point tracking. IEEE Trans. Sustain. Energy 9 (1), 45–55.
- Ji-Ying, S., Fei, X., Zi-Jian, Q., Wen, Z., Le-Tao, L., Ting, Y., 2016. Improved global maximum power point tracking for photovoltaic system via cuckoo search under partial shaded conditions. J. Power Electron. 16 (1), 287–296.
- Jiang, L.L., Nayanasiri, D.R., Maskell, Douglas L., Vilathgamuwa, D.M., 2015. A hybrid maximum power point tracking for partially shaded photovoltaic systems in the tropics. Renew. Energy 76, 53–65.
- Karami, Nabil, Moubayed, Nazih, Outbib, Rachid, 2017. General review and classification of different MPPT techniques. Renew. Sustain. Energy Rev. 68 (1), 1–18.
- Kermadi, M., Berkouk, E.M., 2017. Artificial intelligence-based maximum power point tracking controllers for photovoltaic systems: Comparative study. Renew. Sustain. Energy Rev. 69, 369–386.
- Kok Soon, T., Saad, M., Hong-Tzer, Y., Ming-Kai, C., 2014. A differential evolution based MPPT method for photovoltaic modules under partial shading conditions. Int. J. Photoenergy 2014, 945906, 1-10.
- Madeti, S., Singh, S., 2017. Comparative analysis of solar photovoltaic monitoring systems. AIP Conf. Proc. 1859, 1–6.
- Mirjalili, S., Lewis, A., 2016. The whale optimization algorithm. Adv. Eng. Softw. 95, 51–67.
- Mohanty, S., Subudhi, B., Ray, P.K., 2017. A grey wolf-assisted perturb & observe MPPT algorithm for a PV system. IEEE Trans. Energy Convers. 32 (1), 340–347.
- Mohanty, S., Subudhi, B., Rey, P.K., 2016. A new MPPT design using grey wolf optimization technique for photovoltaic system under partial shading conditions. IEEE Trans. Sustain. Energy 7 (1), 181–188.
- Peng, B., Ho, K., Liu, Y., 2018. A novel and fast MPPT method suitable for both fast changing and partially shaded conditions. IEEE Trans. Ind. Electron. 65 (4), 3240–3251.
- Premkumar, M., Karthick, K., Sowmya, R., 2018. A comparative study and analysis on conventional solar PV based DC-DC converters and MPPT techniques. Indones. J. Electr. Eng. Comput. Sci. 11 (3), 831–838.
- Premkumar, M., Sowmya, R., 2019. Certain study on MPPT algorithms to track the global MPP under partial shading on solar PV module/array. Int. J. Comput. Digit. Syst. 8 (4), 405–416.

- Premkumar, M., Sumithira, T.R., 2018. Humpback whale assisted hybrid maximum power point tracking algorithm for partially shaded solar photovoltaic systems. J. Power Electron. 18 (6), 1498–1511.
- Premkumar, M., Sumithira, T.R., 2019. Design and implementation of new topology for solar PV based transformerless forward microinverter. J. Electr. Eng. Technol. 14 (1), 145–155.
- Priti, D., Mohapatra, A., Nayak, B., 2017. Modeling and characteristic study of solar photovoltaic system under partial shading condition. Mater. Today Proc. 4 (14), 12586–12591.
- Riaz, A., Murtazaa, A.F., Ahmed Sherb, H., 2019. Power tracking techniques for efficient operation of photovoltaic array in solar applications – A review. Renew. Sustain. Energy Rev. 101, 82–102.
- Santi Agatino, R., Giacomo, S., 2015. ANN based MPPT method for rapidly variable shading conditions. Appl. Energy 14, 124–132.
- Sundareswaran, K., Peddapati, S., Palani, S., 2014. MPPT of PV systems under partial shaded conditions through a colony of flashing fireflies. IEEE Trans. Energy Convers. 29 (2), 463–472.
- Sutikno, T., Jusoh, A., Guan, T.K., Mekhilef, S., 2014. A Review on favourable maximum power point tracking systems in solar energy application. Telkomnika 12 (1), 6–22.
- Yi-Hwa, L., Shyh-Ching, H., Jia-Wei, H., Wen-Cheng, L., 2012. A particle swarm optimization-based maximum power point tracking algorithm for PV systems operating under partially shaded conditions. IEEE Trans. Energy Convers. 27 (4), 1027–1035.