

A new meta-heuristic optimization algorithm based MPPT control technique for PV System under diverse partial shading conditions

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A new meta-heuristic optimization algorithm based MPPT control technique for PV System under diverse partial shading conditions

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Abstract

At present, a photovoltaic (PV) system takes responsibility to reduce the risk of global warming and generate electricity. However, the PV system faces numerous problems to track global maximum peak power (GMPP) owing to the nonlinear nature of the environment especially due to partial shading conditions (PSC). To solve these difficulties, previous researchers have utilized various conventional methods for investigations. Nevertheless, these methods have oscillations around the GMPP. Hence, a new metaheuristic method such as an opposition based equilibrium optimizer (OBEO) algorithm is used in this work for mitigating the oscillations around GMPP. To find the effectiveness of the proposed method, it can be evaluated with other methods such as SSA, GWO, and P&O. As per the simulation outcome the proposed OBEO method provides maximum efficiency against all other methods. The efficiency for the proposed method under dynamic PSC is 95.09% in 0.16 seconds similarly, 96.17% for uniform PSC and 86.25% for complex PSC.

Keywords: Photovoltaic (PV); Partial Shading Condition (PSC); Complex partial shading conditions (CPS); Global maximum peak power (GMPP); Opposition based equilibrium optimizer (OBEO).

Nomenclature			
PV	Photovoltaic	P&O	Perturb and Observe
MPPT	Maximum Power Point Tracking	INC	Incremental Conductance
LMPP	Local Maxima Peak Power	FLC	Fuzzy Logic Control
GMPP	Global Maxima Peak Power	ANN	Artificial neural network
MPP	Maximum Peak Power	ACO	Ant Colony Optimization
MPPP	Multiple peak powers points	ABC	Artificial bee colony
PSC	Partial Shading Conditions	BAT	Bat
PS	Partial shading	CS	Cuckoo Search
GP	Global peak	CSO	Cat Swarm Optimization
GO	Global optima	SSA	Salp Swarm Algorithm
LO	Local optima	GA	Genetic algorithm
EO	Equilibrium optimizer	GWO	Grey Wolf Optimization
OBL	Opposition based-learning	MFO	Moth Flame Optimization
OBEO	Opposition based equilibrium optimizer		
PSO	Particle swarm optimization		

1.0 Introduction

Nowadays, spiking the power demand due to the bulk utilization of power consumers such as industries, commercial complexes, transportation of electric vehicles (EVs) and pumping irrigation systems. To fulfil of required power demand, balance the power generation, renewable and non-renewable energy sources are used[1]. In the past decades usually, non-renewable energy resources are used to meet power demand however, these resources produce greenhouse gases moreover these gases are not easily replenished and impact the environment as well[2]. To accomplish these problems, most of the researchers focused on renewable energy resources among those, the solar photovoltaic (PV) system is one of the best alternatives[3]. It has been free from pollution, eco-friendly to the environment and human beings also. The cost of the system also decreased on the account of the development of technology[4]. Moreover, some governments provide subsidies for the installation of solar plants[5]. Due to the encouragement of governments despite the covid19 pandemic, the total solar capacity in the world has increased by more than 260 GW added in the year 2020[6]. PV system converts solar energy into electricity. However, due to the uncertain nature of the

environment, the PV system does not produce a favourable output[7]. To collect the global peak (GP), maximum power tracking techniques (MPPTs) are used which act as a controller[8]. The standard block diagram for the PV system is shown in Figure 1. In this Figure, the MPPT controllers are placed in between the PV system and DC-DC boost converter. The output of the PV system is applied to the MPPT controller as an input. The output of the MPPT controller is given to the boost converter as an input in terms of duty-cycle. Later, the result of boost converter connected to load.

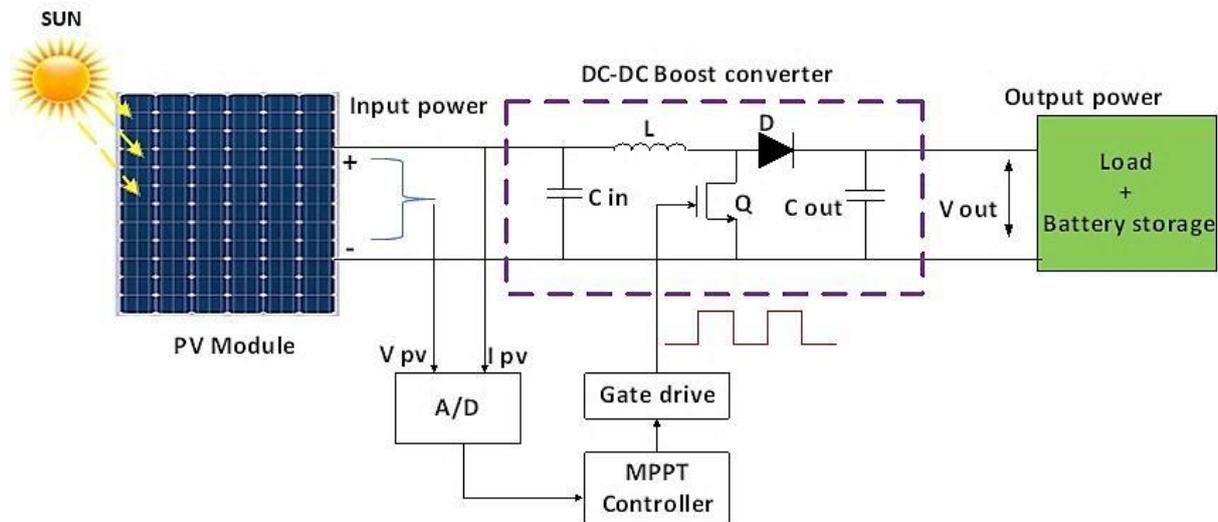


Figure 1. Standard PV system

Initially, the development of MPPTs can be done through conventional methods such as perturb and observe (P&O), incremental conductance (INC), fractional open circuit, and fractional short circuit[9]. These conventional/ traditional methods could track the maxima peak power (MPP) under ideal conditions only and face oscillation around the MPP during the change in weather conditions[10]. Later soft computing methods are used fuzzy logic (FL) and artificial neural network (ANN), able to track MPP with no oscillations even under partial shading conditions (PSC)[11]. The disadvantage of these methods required skilled people to design and maintain aspects results cost of the system increased[12].

Recently, many researchers move to metaheuristic methods to avoid the numerous problems faced by all the above methods. The metaheuristic methods are particle swarm optimization (PSO)[13], ant colony (ACO)[14], artificial bee colony (ABC)[15], bat (BAT)[16], cuckoo search (CS)[17], salp swarm algorithm(SSA)[18], genetic algorithm (GA)[19], grey wolf optimization (GWO)[20] and moth flame optimization (MFO)[21]. The PSO method was able to track the GMPP even under non-ideal conditions and gave a better

result as compared to conventional methods[22]. The disadvantage of this method easily falls into local optima (LO) instead of global optima (GO) and takes a long time to track the MPP[23]. ABC has good exploration ability and tracks MPP under non-ideal conditions, however, suffer from exploitation ability[24]. Later to solve multiple problems BAT method was used, which has good exploitation capability and it belonged to metaheuristic methods. Although this method is not good yet exploration aspect to avoid this problem and to balance the exploration and exploitation needed a separate controller which leads to increase the cost[25]. Both DE and GA methods show identical performance due to their crossover operator[26]. These methods are good in the aspects of time to track the MPP as compared to the BAT method however during the development researchers face a few problems such as complexity, depending on initial population and premature convergence. GWO shows superior performance to track GO as compared to PSO and ABC. The development of GWO mainly depends on four groups such as alpha (α), beta (β), delta (δ), and omega (ω) in a hierarchical manner for the required operation. This method is also not good yet to balance balancing the exploration and exploitation abilities[27]. SSA provide high efficiency as compared to ACO and able track MPP nevertheless, this method required four parameters for the implementation, high oscillation at steady state as compared to BAT and GWO[28]. For all the above methods a comprehensive comparison is presented in Table 1 for easy understanding.

Table 1. A comprehensive comparison between metaheuristic methods

Type of algorithm	Speed of convergence	Efficiency	Oscillation at steady state	Development complexity
OBEO	Very High	Very High	Very low	Medium
PSO[13]	High	High	Low	High
ACO[14]	Medium	Medium	Low	Medium
ABC[15]	Medium	High	Low	High
BAT[16]	Very High	High	Medium	High
CS[17]	High	High	Low	Medium
GWO[27]	High	High	Medium	Medium
SSA[28]	Medium	High	High	High
MFO[21]	High	High	Medium	High

Almost all the above metaheuristic methods are faced with common problems mainly not good yet balancing the exploration and exploitation abilities, time to track MPP, convergence speed and implementation complexity. To escape these problems a new metaheuristic method such as the opposition based equilibrium optimizer (OBEO) algorithm is presented in this paper.

The main contribution from this paper as presented below

- 1.0 Initially design the PV system with 2 series 2 parallel (2S2P) combinations and examine the diverse weather conditions.
- 2.0 The new OBEO method is applied to the proposed PV system to balance exploration and exploitation.
- 3.0 Ascertain the worthier qualities of OBEO against P&O, GWO, and SSA in terms of tracking time, tracking GMPP, and efficiency under PSC.
- 4.0 The proposed OBEO method along with the other three methods are developed in MATLAB/Simulink.

The objectives of this paper along with the introduction is presented in section 1. whereas the design of the PV system and partial shading conditions as well as the basic theory of existing methods are mentioned in section 2. Section 3 describes the proposed OBEO method in a detailed manner. Results and discussion for the proposed methods are illustrated in section 4. At last, the conclusion and its future scope are presented in section 5.

2.0 Design of PV system and partial shading condition

The ideal design of PV system consists of diode and DC source here the diode is connected parallel to the current source whereas diode is placed in antiparallel consequently for the design of practical PV system series and parallel resistance are connected to ideal PV system as shown in Figure 2. Usually, different types of PV systems are available depending on the diode connection such as single diode model, two-diode model, and three diode model among those single diode models is mostly preferred[29]. The main reason behind the preference for a single model is low complexity in the design aspects and easy maintenance[30]. In this paper, the single diode model is used.

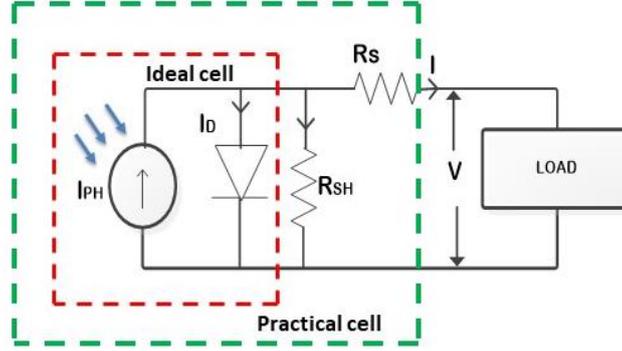


Figure 2. Single diode PV model

The mathematical model of the single diode model is as follows.

$$I = I_{PV} - I_0 \left[\exp \left(\frac{V}{\alpha V_T} \right) - 1 \right] \quad (1)$$

$$I = I_{PV} - I_0 \left[\exp \left(\frac{V+R_S I}{\alpha V_T} \right) - 1 \right] - \frac{V+R_S I}{R_P} \quad (2)$$

$$V_T = \frac{N_S K_T}{q} \quad (3)$$

The below equation represents when no of cells are connected in series (N_S) and parallel (N_P) and is modified from Equ. (2).

$$I = I_{PV} N_P - I_0 N_P \left[\exp \left(\frac{V+R_S I_{eq}}{N_S \alpha V_T} \right) - 1 \right] - \frac{V+R_S I_{eq}}{R_P} \quad (4)$$

For the generation of the high amount of output power from the PV panels need to connect more panels in series and parallel combinations. Under uniform conditions the PV characteristics (i.e I-V and P-V characteristics) produce only one peak power however, the environmental conditions are unstable under PSC[27]. Due to that reason, the PV characteristics produces multiple peak powers points (MPPP) only one is a global peak (GP) and the remaining are local peaks (LP)[31]. The PV characteristics under Partial shadings (PS) are presented in Figure 3. In this paper 2S2P PV system is proposed which is very close to a practical system as shown in Figure 4 and The standard test conditions (STC) for the PV system as shown in Table 2.

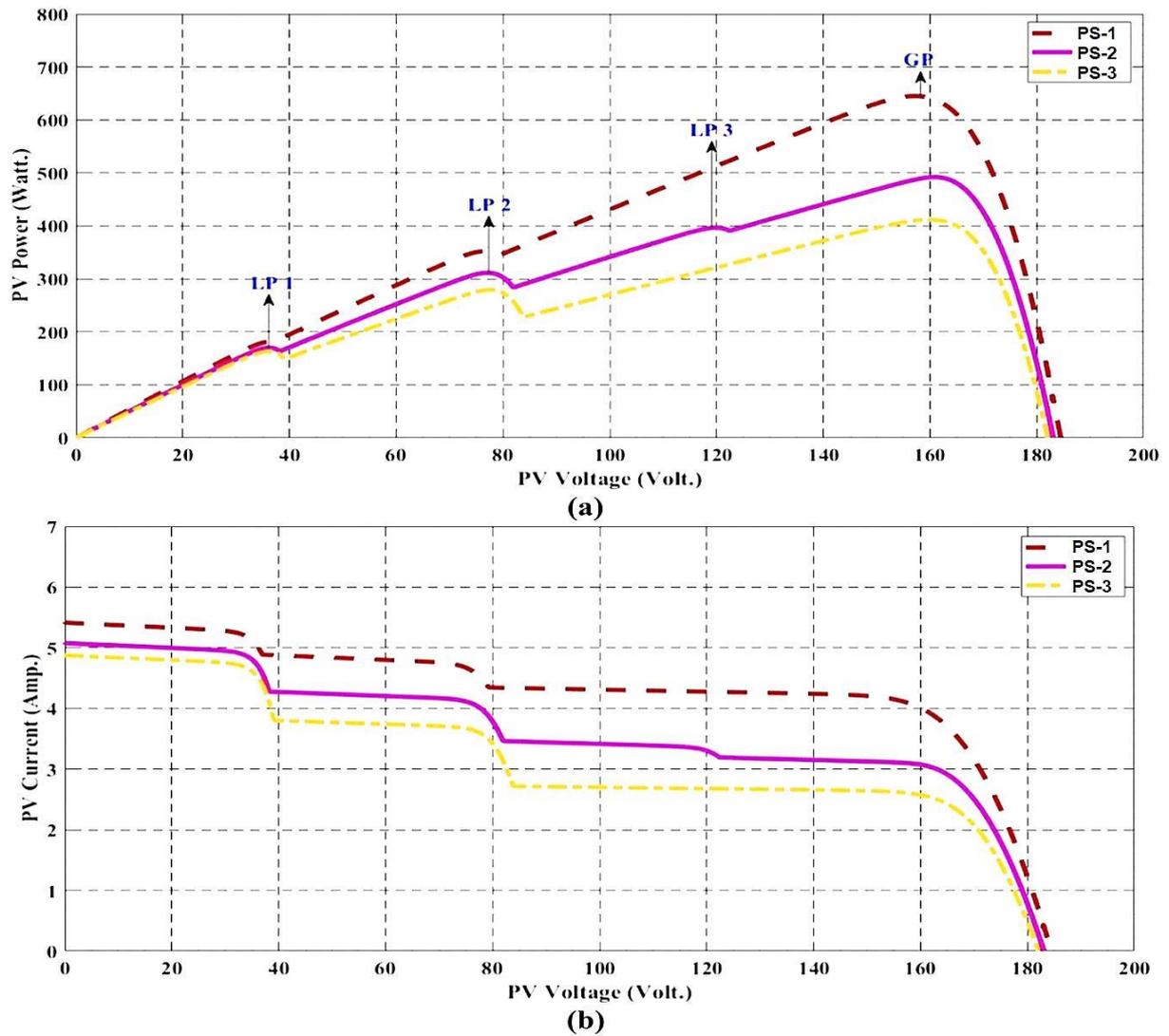


Figure 3. PV characteristics under PSC

Table 2. Standard test conditions (STC) for PV panel

Parameter	Rating
Maximum power (P_{max})	200 W
Voltage at maximum power (V_{mp})	40 V
Current at maximum power (I_{mp})	5 A
Open circuit voltage (V_{oc})	47.8 V
Short circuit current (I_{sc})	6.2 A
Number of cells per module	72

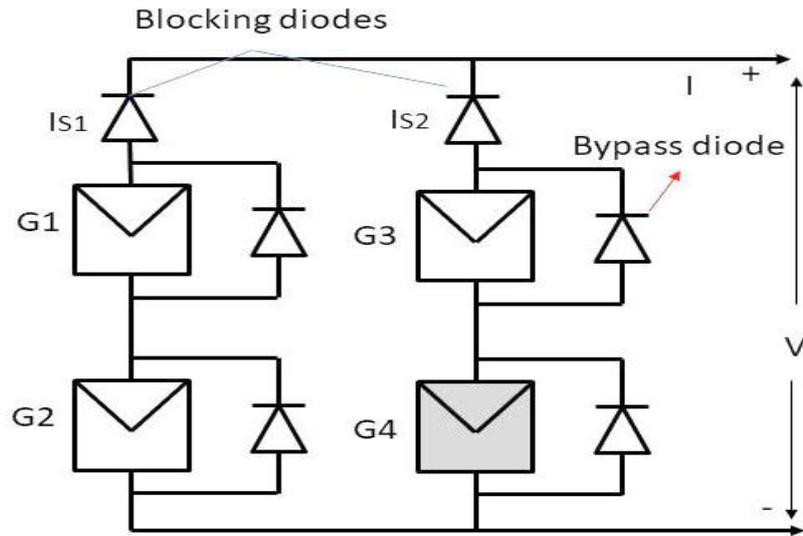


Figure 4. Proposed 2S2P PV system

2.1 Perturb and observe method

This is a conventional method and also be called a hill-climbing method[32]. The working principle of perturbing and observing (P&O) is to vary the voltage or change the duty cycle in a regular interval of time then observes the change power direction to determine the required signal. In the design aspects, this method is easily implemented and reliable besides it can track MPP only under constant change in voltage. However, in practice, the environment has unstable nature due to that this method faces oscillations around the MPP under PSC[33]. To avoid these problems metaheuristic methods are preferred these days.

2.2 Grey wolf optimization

Grey wolf optimization is a metaheuristic method and is easily implemented. It has been used in many engineering problems. GWO reduces the prey behaviour with the cooperation of wolves. This method strictly follows the hierarchical manner, for the operation aspect consists of four groups of wolves such as α , β , δ , and ω [27]. Amongst α group of wolves are the leaders and the remaining β and δ wolves are just as follows α to find the optimal solution. Sometimes β and δ wolves are mutually cooperate to α to ascertain the best solution. Whereas ω is the last group of wolves responsible for balancing the internal population as shown in Figure 5.

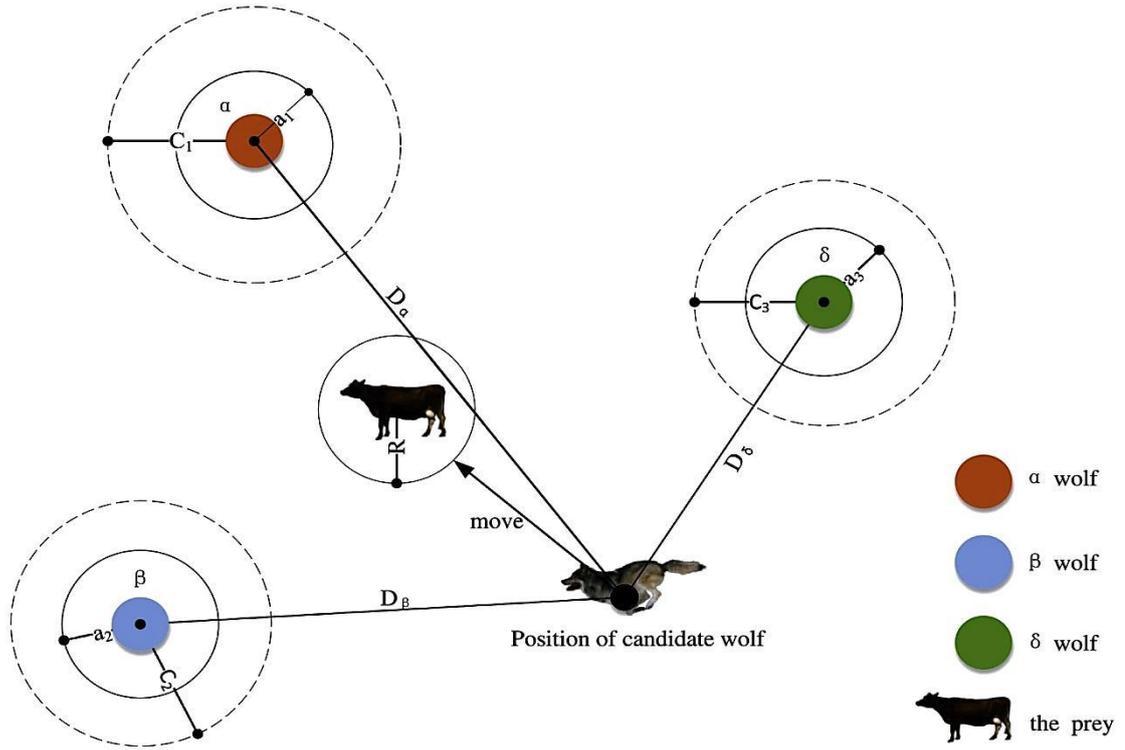


Figure 5. Updating position in GWO [27]

In this method, the prediction process can be divided into three stages encircling, hunting, and attacking.

2.2.1 Encircling

The grey wolves are encircling after the location finding. The mathematical equation for encircling is as follows [27].

$$D_p = |C \cdot X_p(t) - X(t)| \quad (5)$$

$$X(t + 1) = X_p(t) - A \cdot D_p \quad (6)$$

Where A, C, D are the coefficient of vectors and t is the iteration number. $X_p(t)$ is the position of the prey and $X(t + 1)$ is the updated position of the prey.

2.2.2 Hunting

In this stage α , β , δ wolves have hunted the prey and updated the position of wolves[27]. It can be achieved through equations 7 to 9 as shown in Figure 6.

$$\begin{cases} D_\alpha = |C_1 X_\alpha - X(t)| \\ D_\beta = |C_2 X_\beta - X(t)| \\ D_\delta = |C_3 X_\delta - X(t)| \end{cases} \quad (7)$$

$$\begin{cases} X_1 = X_\alpha(t) - A_1 D_\alpha \\ X_2 = X_\beta(t) - A_2 D_\beta \\ X_3 = X_\delta(t) - A_3 D_\delta \end{cases} \quad (8)$$

$$X_p(t+1) = \frac{X_1 + X_2 + X_3}{3} \quad (9)$$

2.2.3 Attacking

At the endstage, the grey wolves are encircling the prey and ready to capture the best solution.

2.3 Salp swarm algorithm

The salp swarm algorithm (SSA) is a metaheuristic method associated with the salpidae family. The shape of the salp has a barrel-shaped body and its tissues are similar to the jellyfish. During the operation, the salps are taken the water into their body then move forward through propulsion nature. The behaviour salp is a swarm nature can be called a salp chain as shown in Figure 6.

The group of salps are classified into two groups a leader and a follower. During the operation, the leader has been placed in front of the salp chain and the remaining are the followers besides the leader supervising the followers[34].

The position of salp is stored in a 2-D matrix called x in which the leader update their position using Equation 10.

$$x_j^1 = \begin{cases} F_j + c_1 \left((ub_j - lb_j)c_2 + lb_j \right) & c_3 \geq 0 \\ F_j - c_1 \left((ub_j - lb_j)c_2 + lb_j \right) & c_3 < 0 \end{cases} \quad (10)$$

Where the position salp with j^{th} dimension is denoted by x_j^1 , the position of food represented by F_j , c_1, c_2, c_3 are the random numbers and ub_j, lb_j are the upper and lower boundaries.

In Equation 10 the coefficients c_1 shows a prominent role to balance exploration and exploitation. Whereas c_2, c_3 are the random numbers used for updating the position.

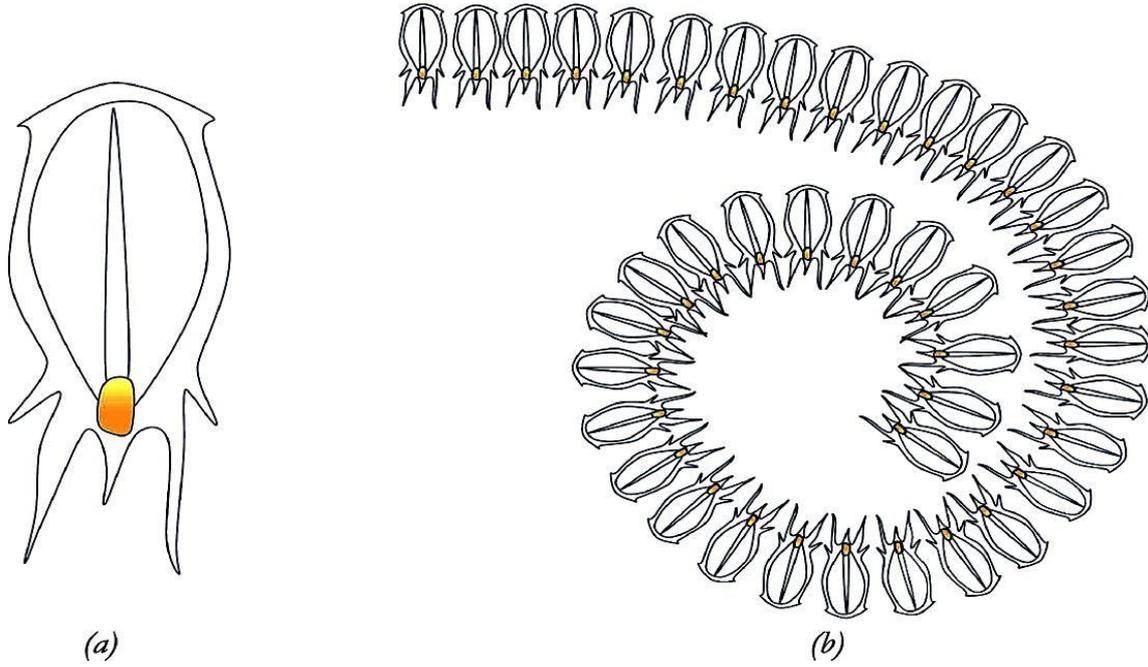


Figure 6. (a) salp (b) salp chain[35]

For update, the followers using Newton's law of motion as follows[34]

$$x_j^i = \frac{1}{2}at^2 + v_0t \quad (11)$$

The iteration time can be optimized by considering the velocity equal to zero from Equation 11 then the result as shown in Equation 12.

$$x_j^i = \frac{1}{2}(x_j^i + x_j^{i-1}) \quad (12)$$

Where the position of follower salp denoted by x_j^i .

The SSA method shows better performance in terms of efficiency, standard deviation, success rate and standard deviation as compared to PSO and MFO. However, still, it has a little bit difficult in time to convergence.

3.0 Opposition-based equilibrium optimizer

3.1 Theory of equilibrium optimizer algorithm

An equilibrium optimizer (EO) is a metaheuristic method that depends on the law of physics and to balance the mass in both dynamic and equilibrium states[36]. This method can solve multi engineering problems like image recognition, power systems and PV parameter estimation. In this paper, EO is used to track the GMPP under diverse partial shading

conditions. To perform the EO method must follow the three stages as shown below.

3.1.2 Initialization

This stage collects the group of particles in which each particle has a solution to optimization problems[36].. In the random search, the initial concentration of vectors is generated by Equation 13.

$$X_i^{\text{initial}} = X_{\text{lb}} + (X_{\text{ub}} - X_{\text{lb}}) \times \text{rand}_i, i = 0,1,2, \dots np \quad (13)$$

Where X_i^{initial} indicates the particle concentration vector, ub,lb are the upper and upper boundries for dimentions, np means number of particles and rand_i denotes random of the i^{th} particle with limits between 0 and 1.

3.1.3 Equilibrium pool and candidates

The EO searches for the equilibrium state. If it is achieved to the near-optimal solution for the optimization problem called equilibrium state[36].. Usually, the EO does not calibrate the concentration level under the optimization process. For that reason, EO allocates the four most productive particle and their arithmetic mean to enhance exploration and exploitation as shown in Equation 14. From this Equation, the equilibrium pool can be obtained and used for generating vectors[36].

$$\vec{D}_{eq,pool} = \{ \vec{D}_{eq,(1)}, \vec{D}_{eq,(2)}, \vec{D}_{eq,(3)}, \vec{D}_{eq,(4)}, \vec{D}_{eq,(avg)} \} \quad (14)$$

During the process, every particle is updated in its concentration for every iteration.

3.1.4 Concentration update

To update the concentration the exponential term (F) is used as shown in Equation 15. This is very useful to update the exploration and exploitation process[36].

$$\vec{F} = e^{-\vec{\lambda}(t-t_0)} \quad (15)$$

Where λ means random vector between the limits 0 and1, t represents the time for the iteration. The t value is decreased with increased iteration.

3.2 Theory of opposition-based learning

To develop, the global optimization opposition based-learning (OBL) was established. Usually, metaheuristic methods provide initial population, random solution and find an optimal solution, however, through the metaheuristic methods ascertaining an optimal

solution takes a long time[37]. To accomplish this problem, the OBL is considered in which opposition is created to the current solution to get the good solution as compared to the previous one and less convergence time to track the GMPP. The opposition to the current solution can be obtained by Equation 16.

$$\bar{x} = ub + lb - x \quad (16)$$

where \bar{x} is the opposition to the current solution. If the \bar{x} is greater than the x then \bar{x} is selected to get the optimum solution.

3.3 Proposed Opposition-based equilibrium optimizer

The major drawback of the basic EO method has easily fallen into local optima (LO) and takes more time for settling to remove these problems opposition direction is considered in which few solutions are prohibited and some particular solutions are changed to a favourable solution. The combination of EO and OBL can be called a proposed opposition-based equilibrium optimizer (OBEO). Adding OBL to EO does not interrupt the basic theory of EO, moreover, increase the efficiency and reduce the time for convergence. The OBL method improves the global optima and updates the evaluation. If the updated solution is greater than the presented solution then follows the updated solution. For easy understanding, the procedure of OBEO is shown in Figure 7.

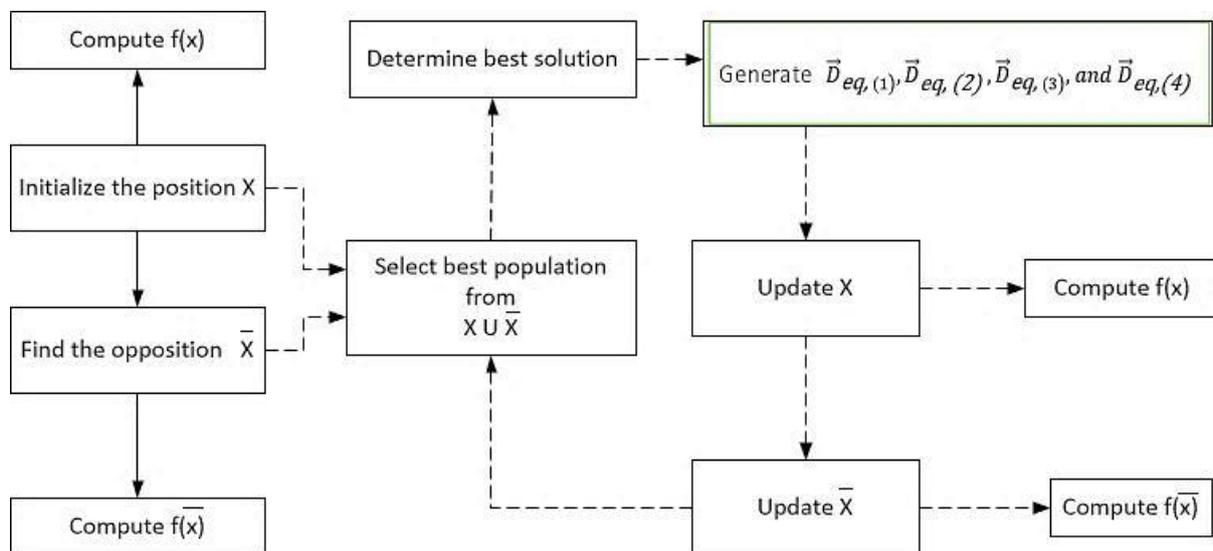


Figure 7. Flowchart for OBEO

The proposed OBEO can balance the exploration and exploitation ability in a less convergence time which is used in this paper to track the GMPP in the PV system under diverse partial shading conditions[38].

4.0 Results and discussion

In this paper, the proposed OBEO method is applied to 2 series and 2 parallel (2S2P) PV systems at different irradiation conditions. The proposed PV system model is close to a practical system. Moreover, the proposed method is compared with other metaheuristic methods such as GWO, SSA and conventional P&O to ascertain the proposed system quality in terms of extracted PV power, convergence time and efficiency. To generate more power, test the proposed system with different components such as PV array, DC-DC boost converter, MPPT controller and load. The specifications for the PV panel is shown in Table 2, design specifications for boost converter are switching frequency, input inductance is 1000 kHz, and 1.7 mH, output capacitance, load resistance are, 100 μ F, and 60 Ω respectively.

The proposed methods are executed in MATLAB/Simulink at diverse partial shading conditions as shown in Table 3. From this Table 3 dynamic PSC is considered as case 1, uniform PSC as case 2 and case3 considered as complex PSC. On the other side, the proposed method is performed for 10 iterations in MATLAB/Simulink. The performance of the system is explained in a casewise manner as shown below.

Table 3. Proposed shading patterns for PV system

Type of case	Shading patterns		
	Pattern #1	Pattern# 2	Pattern #3
Case 1 (Dynamic PSC)	510W/m ²	620 W/m ²	940W/m ²
Case 2 (Uniform PSC)	840 W/m ²		
Case 3 (complex PSC)	900 W/m ² ; 650 W/m ² ; 200 W/m ²		

Case 1: For the proposed PV system, dynamic partial shading conditions are considered such as 510 W/m², 620 W/m², and 940 W/m² as Pattern #1, Pattern# 2 and Pattern #3 with each interval time of 0.5 seconds. To extract the GMPP a new OBEO method is applied along with other metaheuristic methods such as GWO, SSA and one conventional method P&O. The performance of all proposed methods are shown in terms of power, voltage and current with respect to time as shown in Figure 8. From this Figure 8, during pattern#1 the extracted

GMPP for the proposed OBEO method is 612.4 W with 0.102 seconds whereas SSA, GWO and P&O are 480.3 W, 302.6 W and 280.2 W respectively.

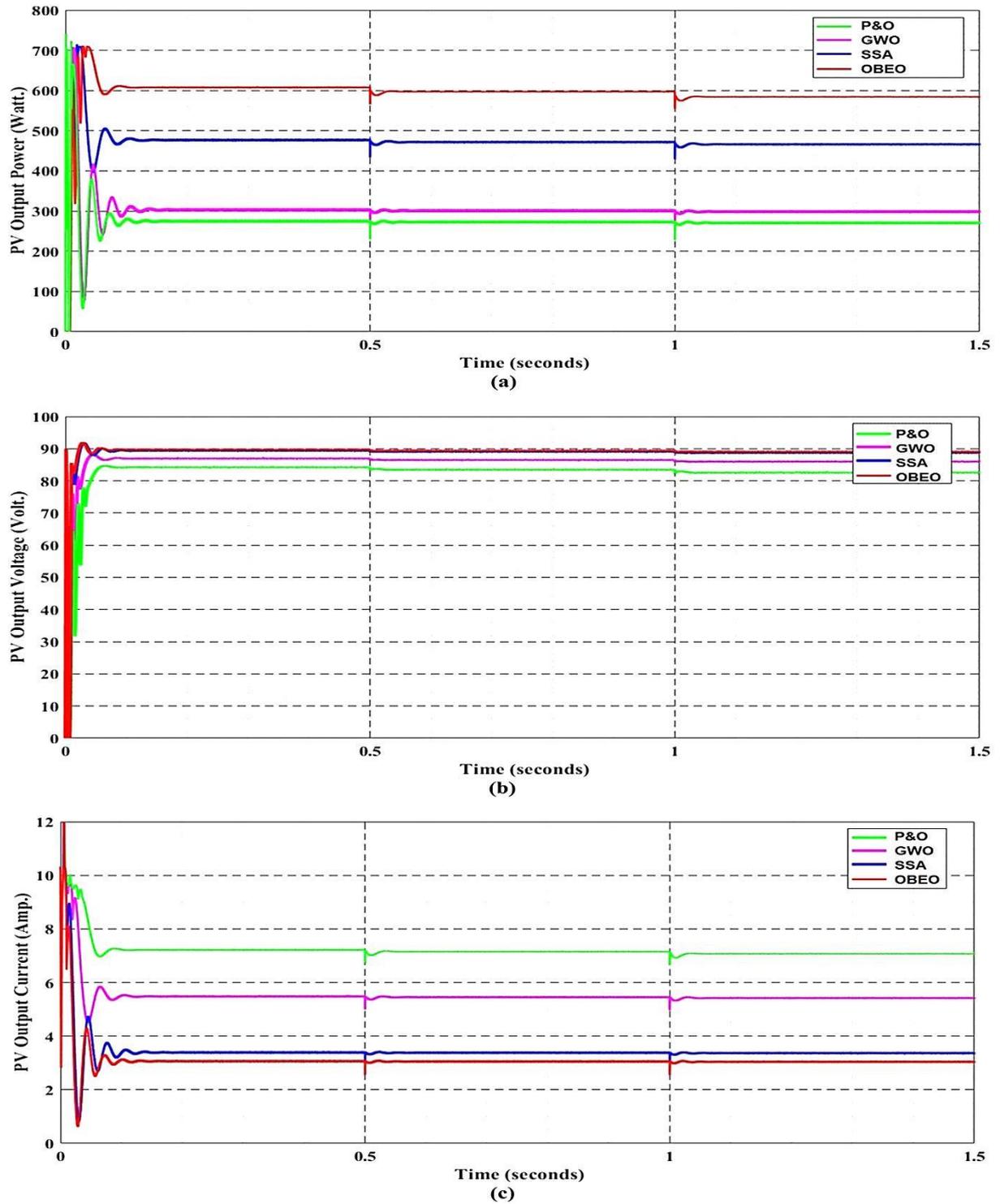


Figure 8. Performance results for OBEO, SSA, GWO and P&O methods under case 1.

For pattern #2 the performance of results is shown in between the time limit of 0.5- 1 seconds as shown in Figure 8. During pattern#2 the OBEO method extracts 599.2 W in 0.126 seconds similarly for the remaining methods such as SSA, GWO and P&O are 476.6 W, 294.2 W and 276.4 W. The GMPP for the proposed method, SSA are 589.6 W and 468.4 W whereas GWO, P&O are 296.3 W and 274.8 W for pattern#3 which is observed between the time limit 1-1.5 seconds.

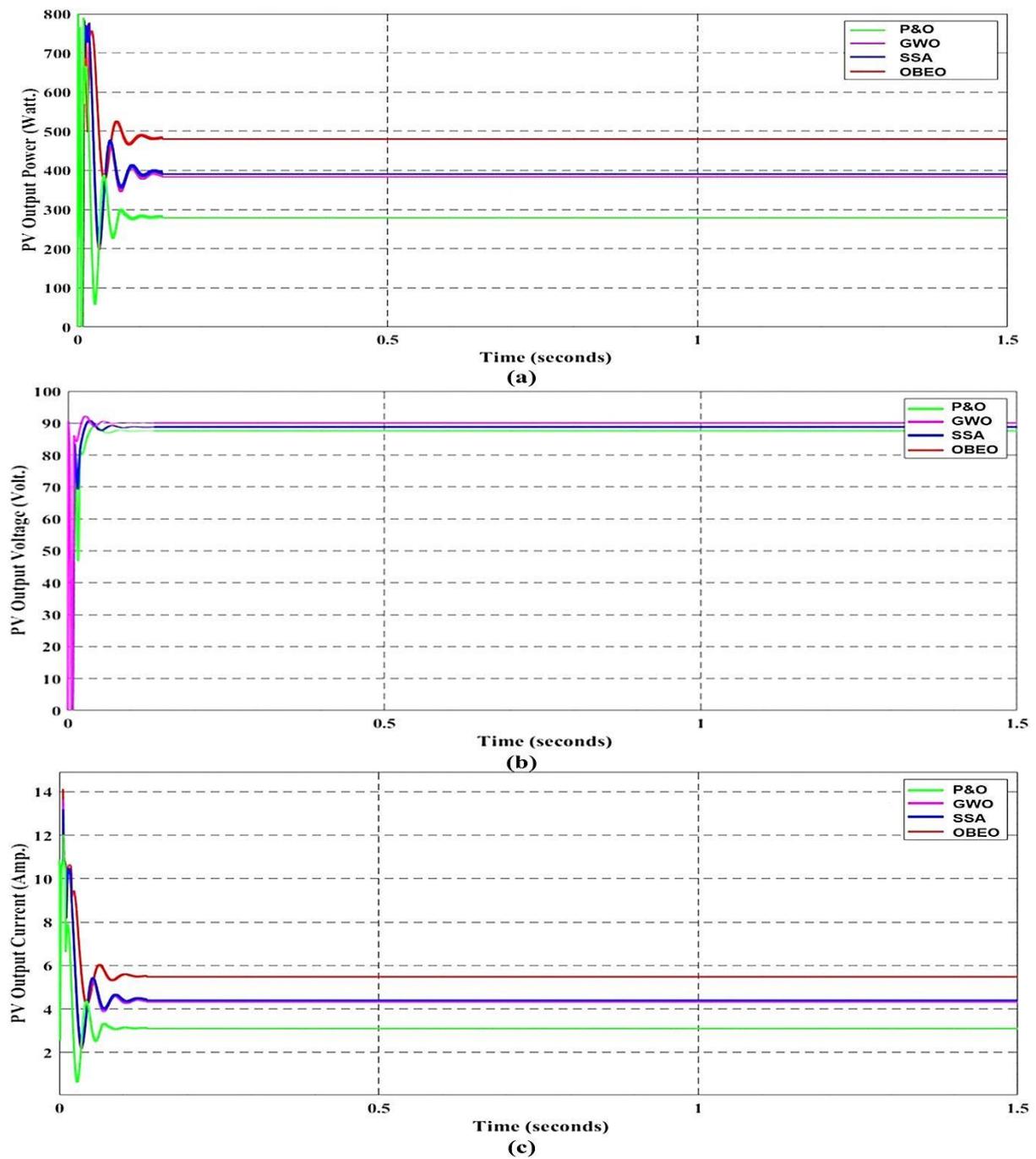


Figure 9. Performance results for OBEO, SSA, GWO and P&O methods at case 2.

Case 2: In this case, uniform partial shading condition 840 W/m^2 is considered then applied all MPPT methods to the proposed PV system. The performance of results is shown in Figure 10 in terms of power, voltage and current. The results indicate proposed OBEO method track maximum power against other methods SSA, GWO and P&O. Moreover, the last two methods such as GWO and P&O provides the least power as compared to OBEO and SSA. The proposed method extracts 490.5W with 0.10 seconds then the corresponding maximum voltage, current values are 87.6 V and 5.6 A respectively as shown in Figure 9. This result shows that proposed method tracks approximately 100 W more power as compared to the SSA method.

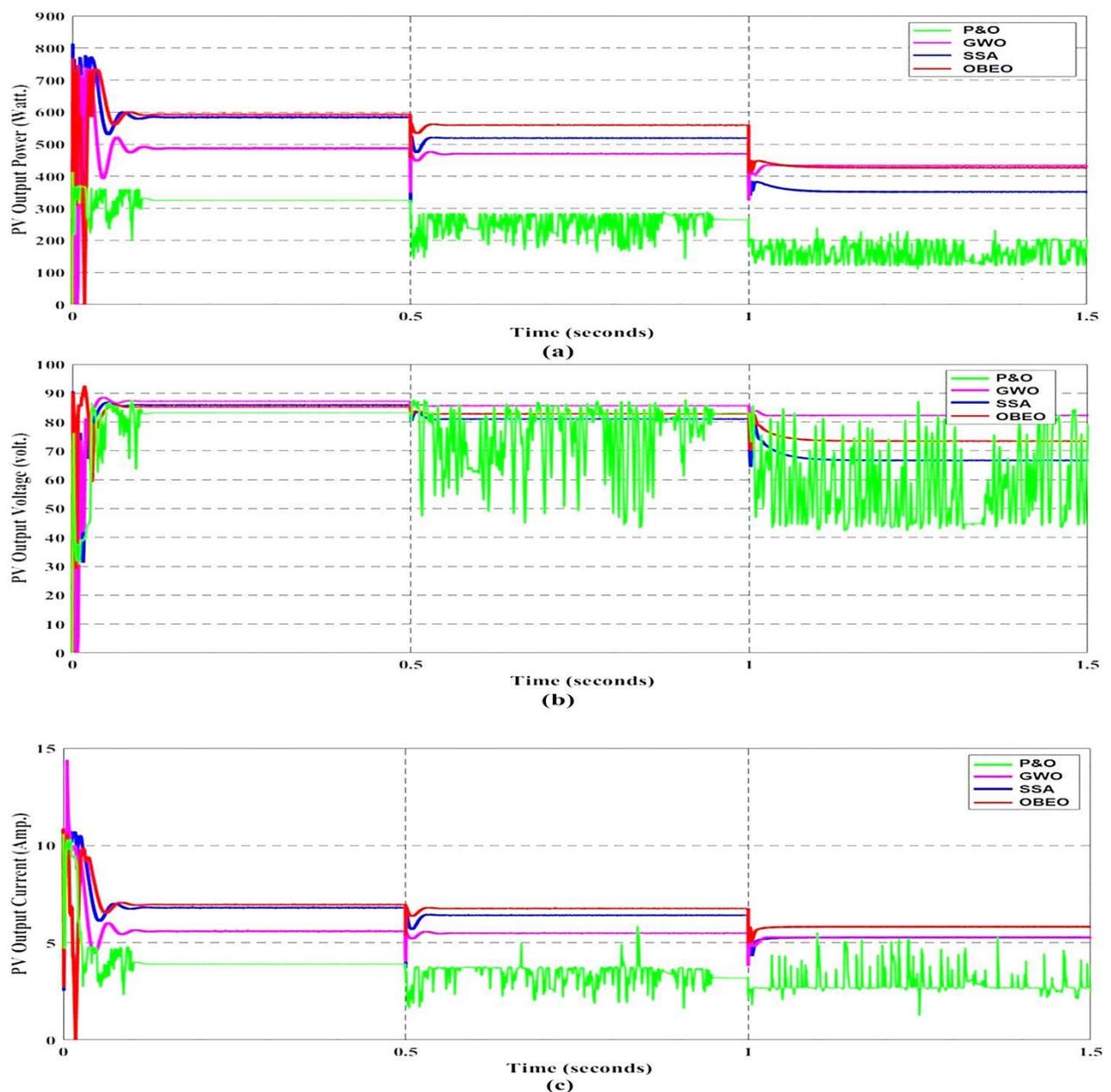
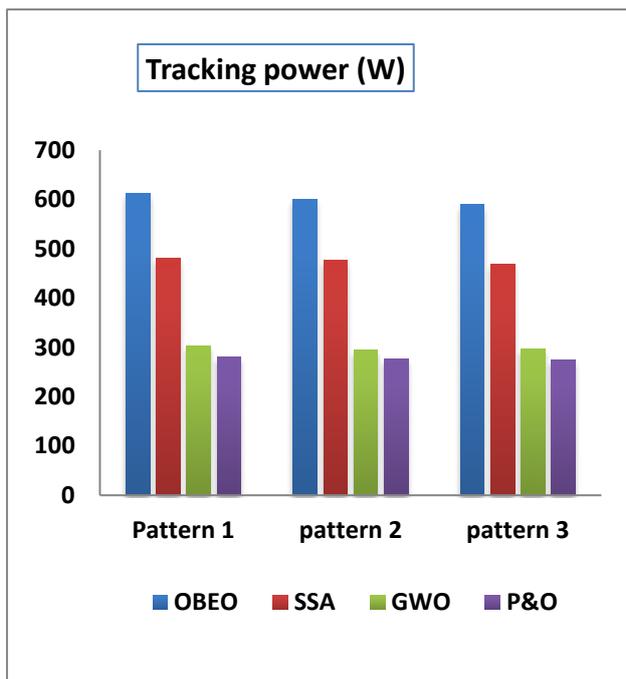


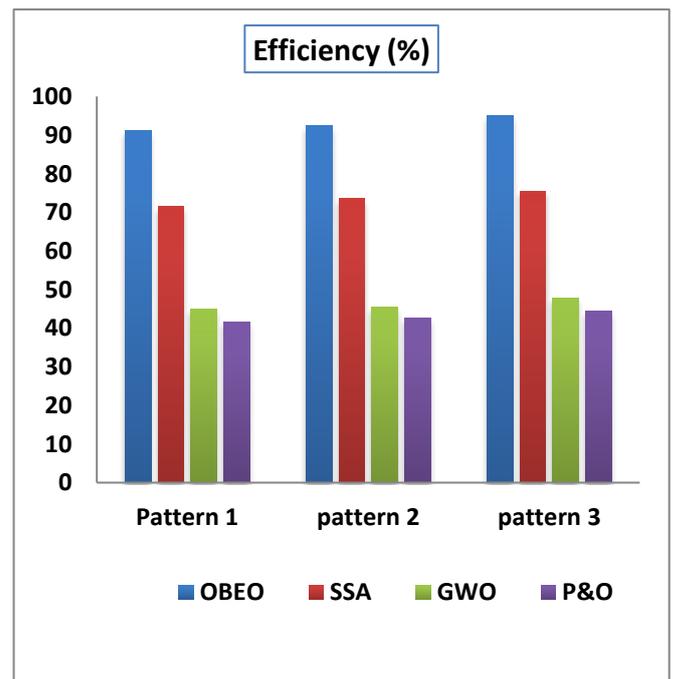
Figure 10. Performance of results under extreme PSC for OBEO, SSA, GWO and P&O

Case 3: At last, the extreme PSCs are applied to suggested PV systems such as 900 W/m^2 , 650 W/m^2 , and 200 W/m^2 . The performance of output results is shown in Figure 10, in which the results are shown for power, voltage and current concerning time. Similar to case 1, here also the shading patterns are created for every 0.5 seconds. In this case 3, the proposed OBEO method provides maximum power with the least power oscillation whereas the conventional P&O gives the least power, as well as large power oscillations during extreme irradianations. The proposed method extracts 582.2 W for 900 W/m^2 , 560.3 W, 420.6 W for 650 W/m^2 , and 200 W/m^2 respectively.

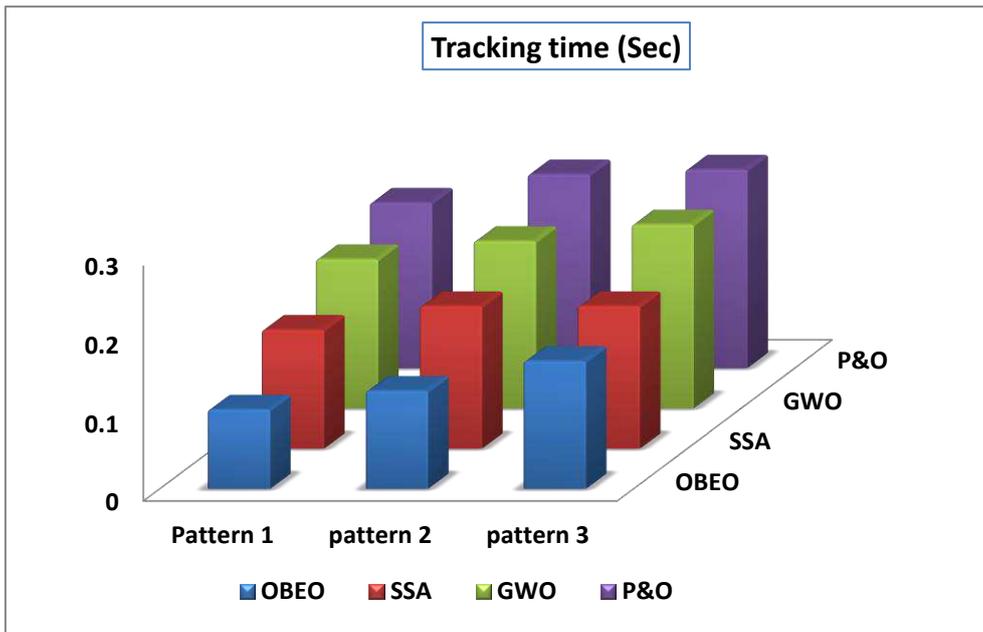
For easy understanding, the performance of the results in terms of tracking power, tracking time, and efficiencies are illustrated in Figure 11 for case 1. Whereas case 2, case 3 are illustrated in Figure 12 and Figure 13.



(a)

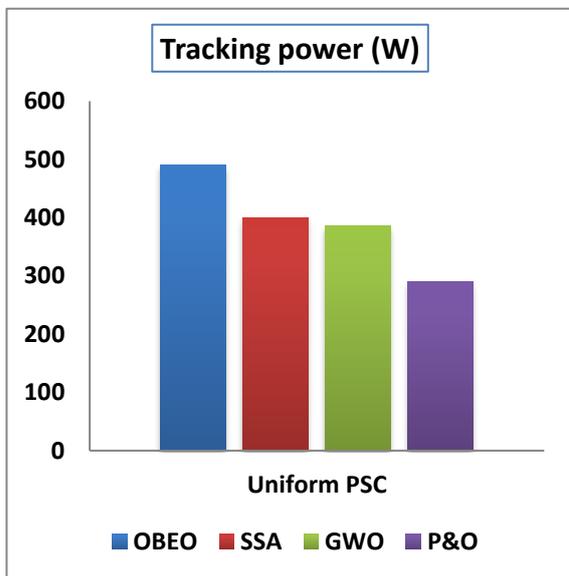


(b)

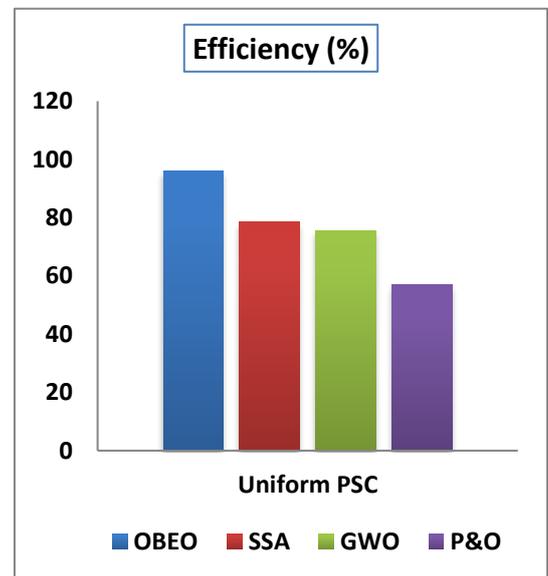


(c)

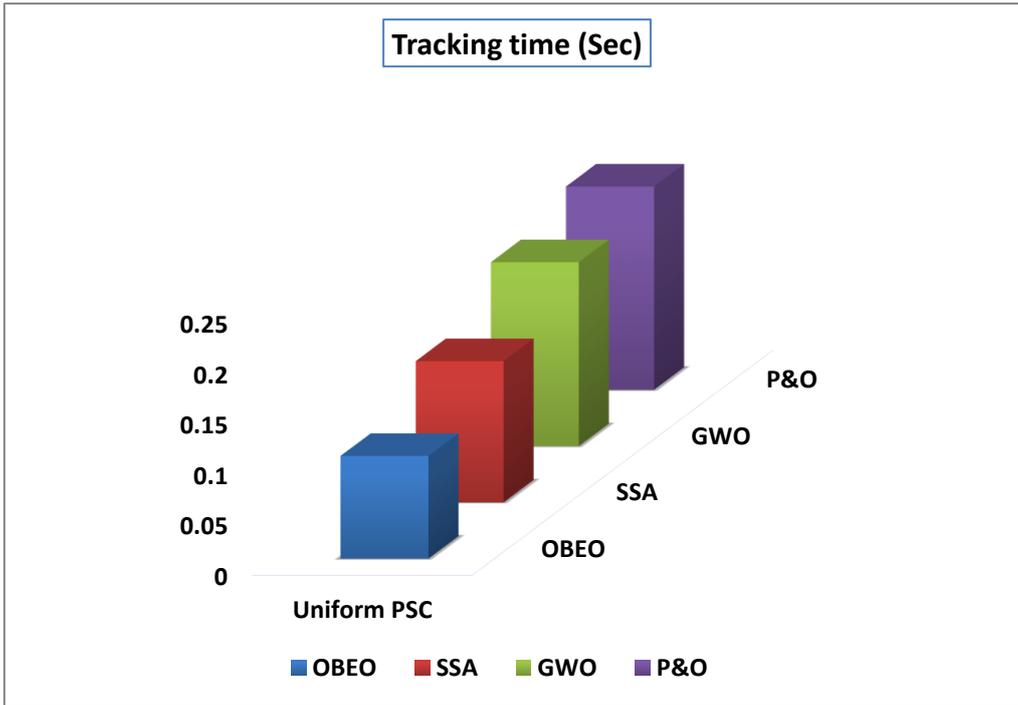
Figure 11. Illustrations for tracking power, efficiency, and time at case 1



(a)

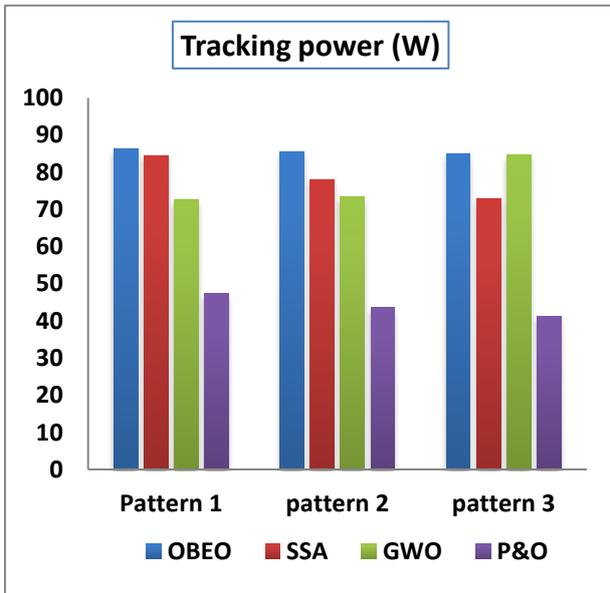


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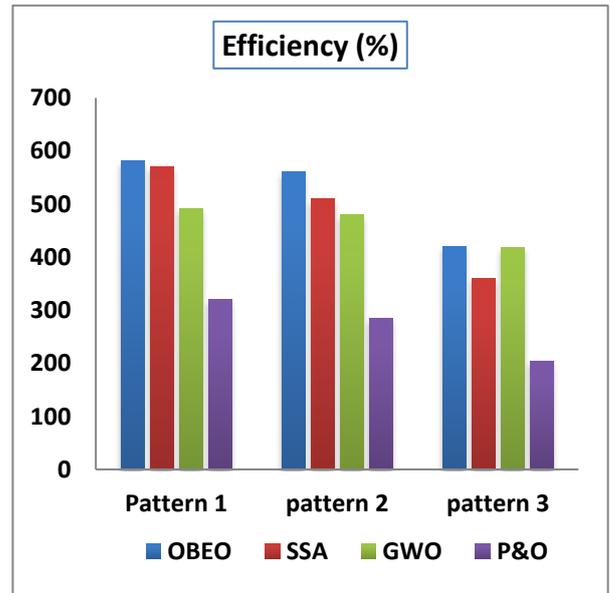


(c)

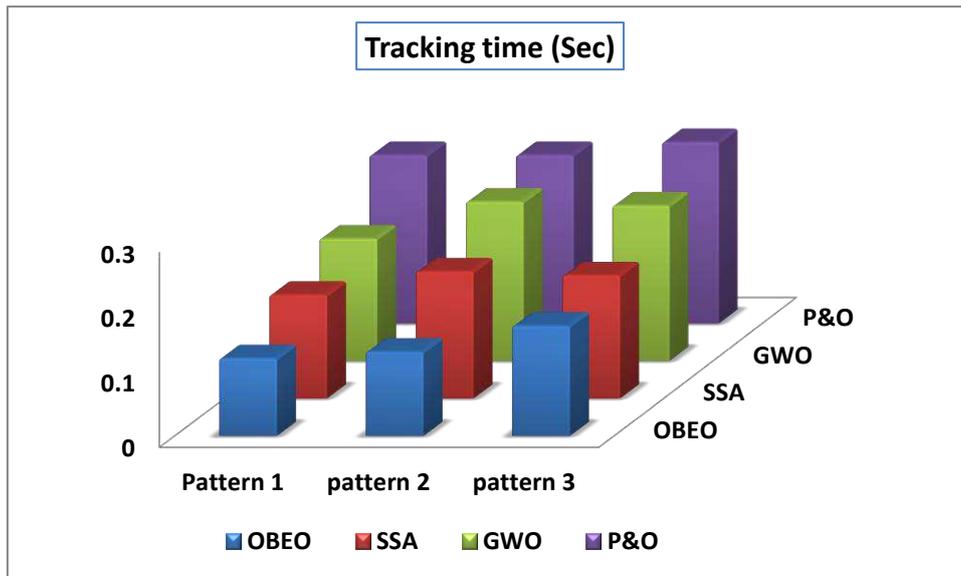
Figure 12. Illustrations for tracking power, efficiency, and time at case 2



(a)



(b)



(c)

Figure 13. Illustrations for case 3

In all cases, the proposed OBEO method extracts maximum power with the least power oscillation irrespective of change in irradiances as against to the other methods SSA, GWO and P&O. Amongst, the conventional P&O method gives a poor performance in the aspects of tracking of power and oscillations. Owing to good exploration and exploitation capabilities the proposed method track GMPP with less time. Moreover, the proposed system is practically applicable to equatorial countries owing to the test conditions being close to equatorial countries' temperatures.

5. Conclusion

In this paper, a new OBEO method is executed to a 2S2P PV system under PSC in a casewise manner. This paper intends to track the GMPP instead of LMPP under PSC. For three cases, the proposed PV system is executed in MATLAB/SIMULINK for 10 iterations and ascertained quality regards tracking GMPP, tacking time, and efficiency. The main contribution of this paper is as follows

- The proposed OBEO method can track the GMPP instead of LMPP under diverse PSC.
- The drawbacks of PSC are analysed and validated in Simulink.

- From the test results, the proposed method provides superior performance among the other three methods such as SSA, GWO, and P&O.
- Moreover, OBEO balances both exploration and exploitation abilities, owing to this tackling of GMPP in less time without any disturbances.

In future, the proposed system will be implemented practically with the optimized cost of converters. Moreover, the proposed system is connected to an on-grid system to maintain the continuity of the power supply to consumers.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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