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# Analysis and Simulation of Bio-Inspired Intelligent Salp Swarm MPPT Method for the PV Systems under Partial Shaded Conditions

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**Abstract:** This paper proposes a new bio-inspired intelligence maximum power point tracking (MPPT) algorithm to abstract the high power from the photovoltaic (PV) array systems with the high tracking efficiency under partial shading conditions (PSC). The algorithm is based on the swarming behavior of salp, and this method locates global peak (GP) with the high convergence speed and high efficiency. The proposed salp swarm (SS) algorithm reduces the computational time than the conventional MPPT algorithms such as whale optimization (WO) algorithm, and perturb and observation (PO) algorithm discussed in the literature. The modeling and simulation is done with Matlab software and validated under PSCs. The simulation result demonstrates the effectiveness of SS algorithm with high tracking efficiency and the high convergence to GP.

**Keywords:** GP, MPPT, partial shading condition, PO, SS, WO

## 1. Introduction

Currently, the renewable energy is widely used in the industry and domestic applications. The solar PV source leads amongst the renewable energy systems due to the merits such as no pollution, no fuel cost, zero gas emission, and ease of maintenance. But, the conversion efficiency of the PV cell is low due to the operating conditions such as a cell temperature, PSC, and drastic change in irradiation. Under PSCs, the PV array system exhibits many local peak (LP), and single GP [1]-[3].

The conventional MPPT techniques fail to track the GP, and the modern MPPT methods are used to counterbalance the effects due to PSC by adjusting the duty cycle of the dc-dc converter to locate the maximum peak power (MPP) in the PV array [4]. The author of [5]-[6] deliberates the conventional algorithms such as PO, and incremental conductance (IC). The results given by both the algorithm is same during the static and dynamic condition of the PV system. The IC and PO algorithm be unsuccessful to trace the GP. The author of [7] presents a modified PO algorithm for the PV based power generation systems. It provides a high convergence rate to GP during a change in environmental operating conditions. The author of [8] presents a modified IC algorithm which is suitable for the PV generation system under PSCs, and several load condition to track the GP, and thus reduction in power losses.

The modern computing based MPPT algorithms uses heuristics, meta-heuristic and an evolutionary algorithm based on bio-inspired or nature-inspired or artificial intelligence such as Artificial Neural Network (ANN), Fuzzy Logic Control (FLC), Particle Swarm Optimization (PSO), Genetic Algorithm (GA), differential evolution, Tabu search, Simulated Annealing (SA), Flower Pollination Algorithm (FPA), firefly, artificial bee colony (ABC), Teaching-Learning (TL) based optimization, Ant Colony Optimization (ACO), etc. [9]-[14]. The author of [15] discussed ABC algorithm to trace the MPP under change in environmental operating conditions with very less parameters, and the convergence rate is self-regulating. Moreover, the author of [16] presents a Cuckoo Search Algorithm (CSA) to track the MPP proficiently under PSC, but the convergence time is more. The author of [17] proposed a WO algorithm to locate the GP, and it compromises high accuracy and tracking speed under the PSCs. The WO is greater in accuracy and tracking speed compared to well-known PSO and ANN techniques.

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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 the high convergence rate [18]. The author of [19] combines the grey wolf optimization (GWO) and PO to achieve the improved 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 primary objective of this paper is to achieve the high tracking speed with high tracking efficiency under PSCs by adjusting the duty cycle of the dc-dc converter. The conventional MPPT algorithms such as PO, WO, GWO, IC, ANN etc. face the glitches to fulfill the above requirements. So, this paper presents a new intelligent MPPT algorithm for the PV power generation system under PSCs to find the GP and increases the stability. This paper is organized as follows. Section 2 presents the PV modeling and its operating characteristics under the change in environmental condition. The SS algorithm modeling and its application to the MPPT is deliberated in section 3. Section 4 presents the simulation and further discussions. Section 5 concludes the paper.

## 2. Modelling and Characteristics of the PV System under PSCs

### A. *Modelling of the PV Panel*

The PV cell is mathematically modelled and the equivalent circuit is similar to the one diode model, and the same is shown in Fig.1 [20]. First, the PV cell is modeled, and then prolonged to the PV panel. The cell current of the one diode model is given in (1).

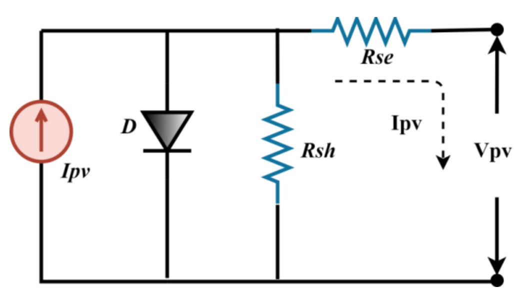


Figure 1. Equivalent circuit of the PV cell.

$$I = I_{PV} - I_0\left[\exp\left(\frac{V+IR_s}{nV_T}\right) - 1\right] - \left[\frac{V+IR_{se}}{R_{sh}}\right] \quad (1)$$

Where the diode saturation is $I_0$, and $V_T$ is the thermal leakage voltage, and n is an ideality factor of the diode. The PV cell is exposed to the change in irradiation and temperature and further the effect on the solar PV is presented as per (2).

$$I_{PV} = \left(I_{pv\_STC} + K_I\Delta T\right)\frac{G}{G_{STC}} \quad (2)$$

Where the photocurrent under standard test condition (STC) is $I_{pv\_STC}$, the change in temperature is denoted by $\Delta T = T - T_{STC}$, $G_{STC}$ is the solar irradiation under STC, i.e. 1000W/m², G is the actual solar irradiation on the PV cell, $K_I$ is the temperature coefficient and the value will be provided by the manufacturer. The thermal leakage voltage equation is given in (3), in which $N_{se}$ represents the series-connected cells in the PV panel.

$$V_T = N_{se}kT/q \quad (3)$$

The above eqautions are suitable for the PV cell, and it is prolonged to the PV module. In PV module, the PV cells are connected in series/parallel combinations to meet the demand. The voltage demand encountered by series-connected cells, and the current demand encountered by parallel-connected cells. The total PV current is presented in (4). The series-connected cells and parallel-connected PV cells are represented as $N_s$ and $N_p$ respectively.

$$I = I_{PV}N_p - I_0N_p\left[\exp\left[\frac{V+IR_{se}\left(\frac{N_s}{N_p}\right)}{nV_TN_s}\right] - 1\right] - \left[\frac{V+IR_{se}\left(\frac{N_s}{N_p}\right)}{R_{sh}\left(\frac{N_s}{N_p}\right)}\right] \quad (4)$$

The PV panel is modeled using (1)-(4) and simulated using MATLAB/Simulink and the simulation results under PSC is shown in Fig. 2. Fig. 2 validates the V-I and P-V characteristics of the PV system under PSCs.

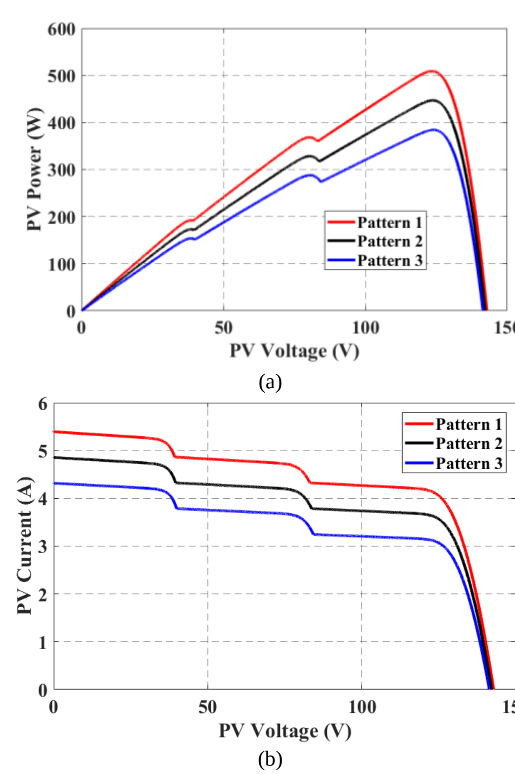


Figure 2. PV panel characteristics under PSCs; (a) P-V characteristics, (b) V-I characteristics.

### *B. Effect on the PV System due to PSCs*

If the PV cells are partially shaded, the cell is subjected to shading and it absorbs high energy due to the reverse bias voltage and the same is transformed as a hotspot and results in thermal stress and, it harm the PV cell. This effect is reduced by bypass diode, and it is connected across the PV module to avoid the negative voltage [21]. The effect on the PV array due to PSC is shown in Fig. 2. Fig. 2(a) shows the P-V characteristic with multiple LP and one GP during shading condition. The various PV array configuration such as series, parallel, series/parallel, total-cross-tied (TCT), honey-comb (HC), and bridge-linked (BL) are discussed in various literatures. To validate the algorithm proposed in this paper, 3S configuration (three series-connected panels) is selected. However, the proposed algorithm in this paper is also suitable for other PV array configurations. The pictorial representation of the PV configurations is shown in Fig. 3. The power generation from the PV panel is expressed as critical issue, and (5) presents the optimized problem.

$$\text{Maximize the power subjected to } d_{min} \leq d \leq d_{max} \quad (5)$$

Where the duty cycle of the dc-dc converter is d, $d_{min}$ characterizes the minimum duty ratio; the maximum duty ratio represented by dmax. The maximum value is fixed at 75% to diminution the reverse recovery on the diode and switching device.

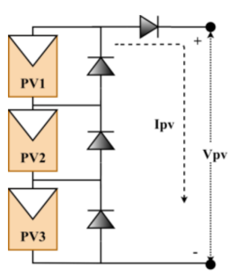


Figure 3. 3S PV array configuration.

## 3. OUTLINE OF THE SALP SWARM MPPT METHOD

### *A. Inspiration of Swarming Behavior of Salp*

The shape of salps is barrel-shape and it has transparent body. The salps tissues are like jellyfishes. Like a jellyfish, the salps are moving and it moves forward by pushing the water through the body like propulsion. Fig. 4 shows the shape of the salp chain. The exciting behaviour of the salp is the key inspiration of this paper, i.e. the swarming behavior of the salp. In the ocean, the salp forms a chain called as salp chain [22]-[23] and the same is shown in Fig.4. Yet, the reason for salp chain is unknown fact to the researchers. Some researchers believes that the chain formation is used for improved movement using change in coordination and foraging.

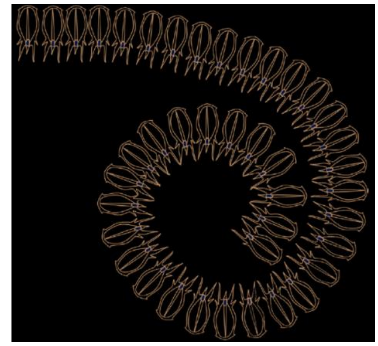

Figure 4. Shape of the salp - salp chain.

### *B. Modeling of the Salp Chain*

The modeling is proposed by [24]-[26], and it is done by separating the population into follower and leader. The forward salp is called a leader, and the left over salps are called as a follower. A leader managing the swarm and the followers follows the leader. Similar to other methods, the position of salp is distinct as n-dimensional search space. The position of the salp is put away in a two-dimensional search space. The swarm target is presumed as source of food in the search space. The position of the leader is updated as per (6).

$$x_j^1 = \begin{cases} F_j + c_1\left(\left(ub_j - lb_j\right)c_2 + lb_j\right) & c_3 \geq 0 \\ F_j - c_1\left(\left(ub_j - lb_j\right)c_2 + lb_j\right) & c_3 < 0 \end{cases} \quad (6)$$

Where the leader position is expressed as $x_j^1$, $F_j$ represents the food source, upper and lower limit is presented as $ub_j$ and $lb_j$ respectively, $c_1$, $c_2$ and $c_3$ are the random numbers. As per (6), the position of the leader is updated about the food source. The $c_1$ is a significant coefficient, and it decides the exploitation and exploration phase. Equation (7) represents the significant coefficient, $c_1$.

$$c_1 = 2e^{-\left(\frac{4l}{L}\right)^2} \quad (7)$$

Where the maximum iteration is L and l is the current iteration. $c_2$, and $c_3$ are generated randomly between [0,1]. The follower position is updated using (8).

$$x_j^i = \frac{1}{2}at^2 + V_o t \quad (8)$$

Where the follower position is expressed as $x_j^i$, $V_o$ is the initial speed, $a=V_{final}/V_o$, and $V=x-x_o/t$. Assume $V_o=0$, inconsistency between the iteration are equal to 1. Equation (8) is altered as (9). The salp-chain is modeled using the above equations.

$$x_j^i = \frac{1}{2}\left(x_j^i + x_j^{i-1}\right) \quad (9)$$

*C. Application of SS Algorithm to PV MPPT*

The key motivation of the algorithm is to find GP instead of LP. In the model, the follower follows the leader, and the leader move towards the food source. If the GP replaces the food source, the chain goes towards the GP. So far the best solution is GP, and the chain hunts the food source. Fig. 5 shows the flowchart of the proposed SS algorithm. It starts with approximate GP by passing on the random position. This finds the fitness, and determines the best fitness, and the position of the best fitness is assigned as a food source. At every dimension, the leader salp position, and follower position is updated as per (7)-(9). If the position of salp is out of search space, it brings back to the boundaries.

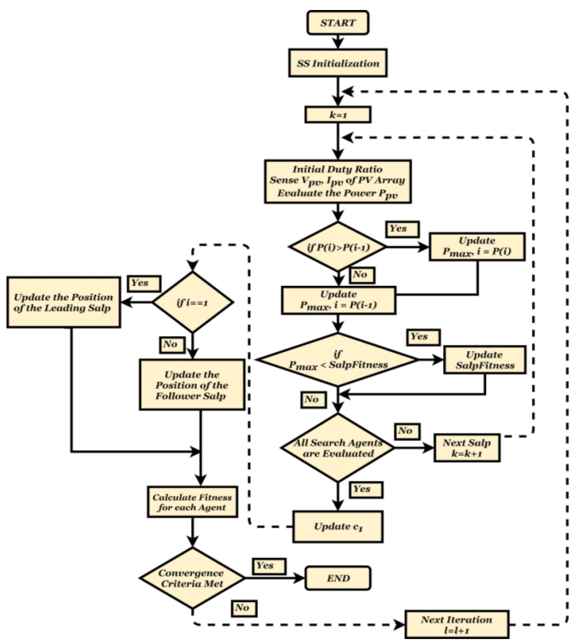


Figure 5. Overall flowchart of the proposed SS MPPT method.

All the steps are repetitive until the criteria for the convergence. The food source is updated due to the salp swarm is likely to find the best solution by exploiting and exploration phase within the search space. The salps move in the direction of the GP that change during each iteration. The position of leader represents the duty cycle for the dc-dc converter which neglects the usage of the PI controller. It aids to diminish the burden on the gain tuning.

Fig. 6 presents the overall block diagram for the proposed method. The power of the PV array changes under the change in environmental condition. During the change in environmental condition, the SS algorithm is reinitialized by calculating the PV power. The efficiency of the dc-dc converter is enlarged by the choosing more number of search agents (salps). To reduce the computation, 15 numbers of salps in a chain are selected in this paper.

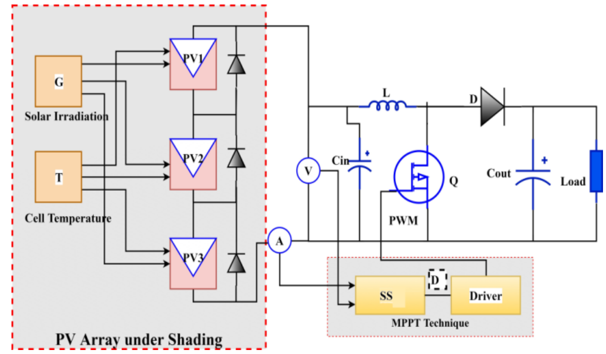


Figure 6. Block diagram of the proposed SS MPPT technique.

## 4. Simulation Results and Discussions

The proposed SS MPPT algorithm is validated by simulating the PV array system using Matlab/Simulink and the comparison between SS, WO & PO is presented in this section. The 3S PV array configuration is selected for testing the SS algorithm under PSCs. The various shading configuration is presented in Table 1. For each 0.2 sec, the shading pattern is changed to test the success in tracking.

TABLE I. SHADING PATTERN FOR THE PV ARRAY SYSTEM

| Shading Pattern | Pattern 1 | Pattern 2 | Pattern 3 | Pattern 4 |
|---|---|---|---|---|
| **Solar Irradiation ($W/m^2$)** | 400 | 500 | 600 | 800 |
| **Insolation Condition** | Rapid Change in Insolation | | | PSCs |
| **Extreme change in insolation** | 200 $W/m^2$ – 400 $W/m^2$ – 600 $W/m^2$ – 800 $W/m^2$ | | | |

The PV system is made with PV array, dc-dc converter, MPPT controller, and the load. The specification of the PV module is as follows: $V_{oc}$ = 47.8V, $I_{sc}$ = 5.4A, $P_{max}$ = 200W, $I_{mpp}$ = 5A, $V_{mpp}$ = 40V, number of cells = 72. The parameters of the dc-dc converter are as follows: $V_{in}$ = (40-100)V, $V_{out}$ = 385V, L = 1.45mH, $C_{out}$ = 470μF, 450V (electrolytic), $C_{in}$ = 100 μF, 100V (electrolytic). The computation time of the SS algorithm is depends on the various other parameters.

*A. PV System under Rapid Insolation Change*

The simulated waveform of the PV power, voltage and current for 3S configuration under rapid change in insolation is presented in Fig. 7. Fig. 7 presents the tracking power and the respective output voltage, and the output current. However, for reader's simplicity, the output power has been explained for each of the shading pattern. As discussed earlier, the shading pattern-1 at 0.2 sec, pattern-2 at 0.4 sec, and the pattern-3 at 0.6 sec are created. During pattern-1, the SS technique converges to GP at 296.8 W, PO locates the GP at 280.2 W, and WO locates the GP at 305.1 W. The pattern-1 is changed to the pattern-2 at 0.4 sec. During pattern-2, the SS method locates the GP at 345.8 W, PO locates the GP at 326.3 W, and WO locates the GP at 311.6 W. During the shading pattern-3, the SS technique locates the GP at 527.4 W, PO locates the GP at 377.5 W, and WO locates the GP at 499.4 W. It is obeserved from the Fig. 7, the WO & PO technique be unsuccessful to locate the GP accurately, and concluded that the SS algorithm displays a high speed in tracking, and the power oscillation is less compared to PO and WO techniques. To end with, the SS algorithm locates the GP accurately with higher convergence speed than the other two algorithms.

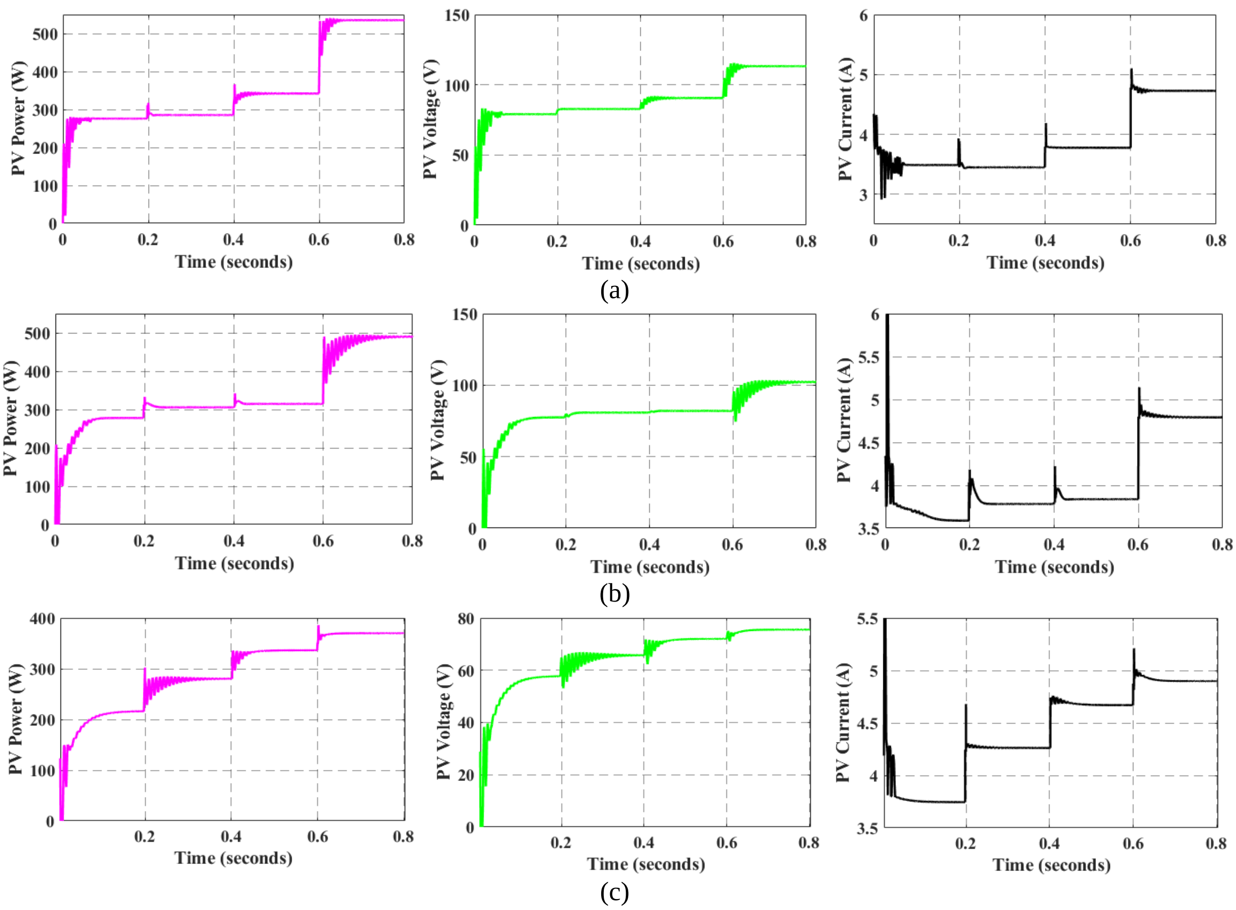


Figure 7. GP tracking characteristics; (a) SS, (b) PO, (c) WO.

### B. PV System under Partial Shading Conditions

The PV power system is simulated under partial shading condition and shading pattern-4 is created as per the Table 1, and the comparison between the different techniques is shown in Fig. 8. From the Fig. 8, it is observed that the SS algorithm locates the MPP at 525.3 W with high tracking speed; say the tracking time is 0.4 sec. But, WO takes 0.85 sec to reach the MPP at 489.4 W, and the PO algorithm takes 0.75 sec to track the MPP at 435.2 W. The SS algorithm tracks high output power from the PV array configuration. The PO and WO track the MPP at almost same convergence speed with less output power than the SS algorithm. The SS algorithm locates and upholds the maximum power with a smaller amount of power oscillation during the PSCs. It gives higher convergence speed than the other algorithms as discussed in the various literatures.

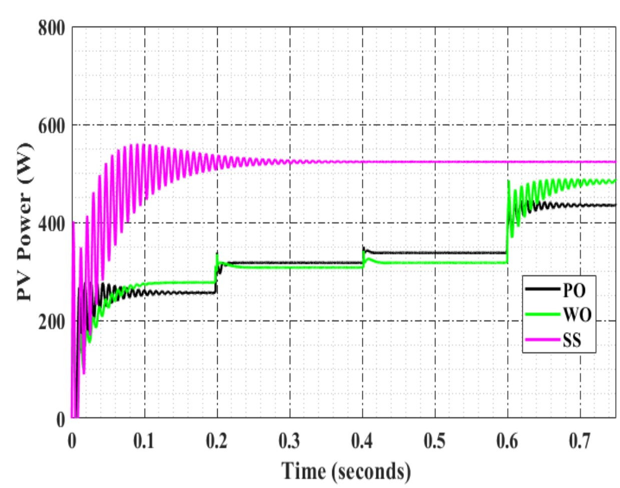


Figure 8. Characteristics of PV array - PV output power for three MPPT techniques.

### *C. PV System under Extreme Insolation Change*

The performance of the SS technique is tried under extreme insolation change to discover the success of the proposed technique when tracks the MPP. The PV output characteristic is shown in Fig. 9. The insolation change is done every 0.2 sec. Figs. 9 (a)-(b) shows the PV characteristics for 3S PV array configuration during rapid insolation change and extreme insolation change respectively. From the Figs. 9(a)-(b), the power convergence is similar in both the SS and WO technique up to 0.4 sec; however, the convergence speed of WO is less than the SS algorithm. From 0.6 sec to 0.8 sec, the power generated from the PV system is 60 W greater when the converter is implemented with SS algorithm. During the insolation change, the PO algorithm produces more power oscillation with less speed and the tracking efficiency. From the above discussions, it is concluded that the SS algorithm based MPPT method can handle the different environmental operating conditions such as a rapid, PSCs, and extreme insolation changes. Due to the local and global search coordination around search space, the SS algorithm maintains high stability and it reduces the power oscillation of the PV power system effectively during various operating conditions. Moreover, the SS algorithm can produce high energy from the PV array.

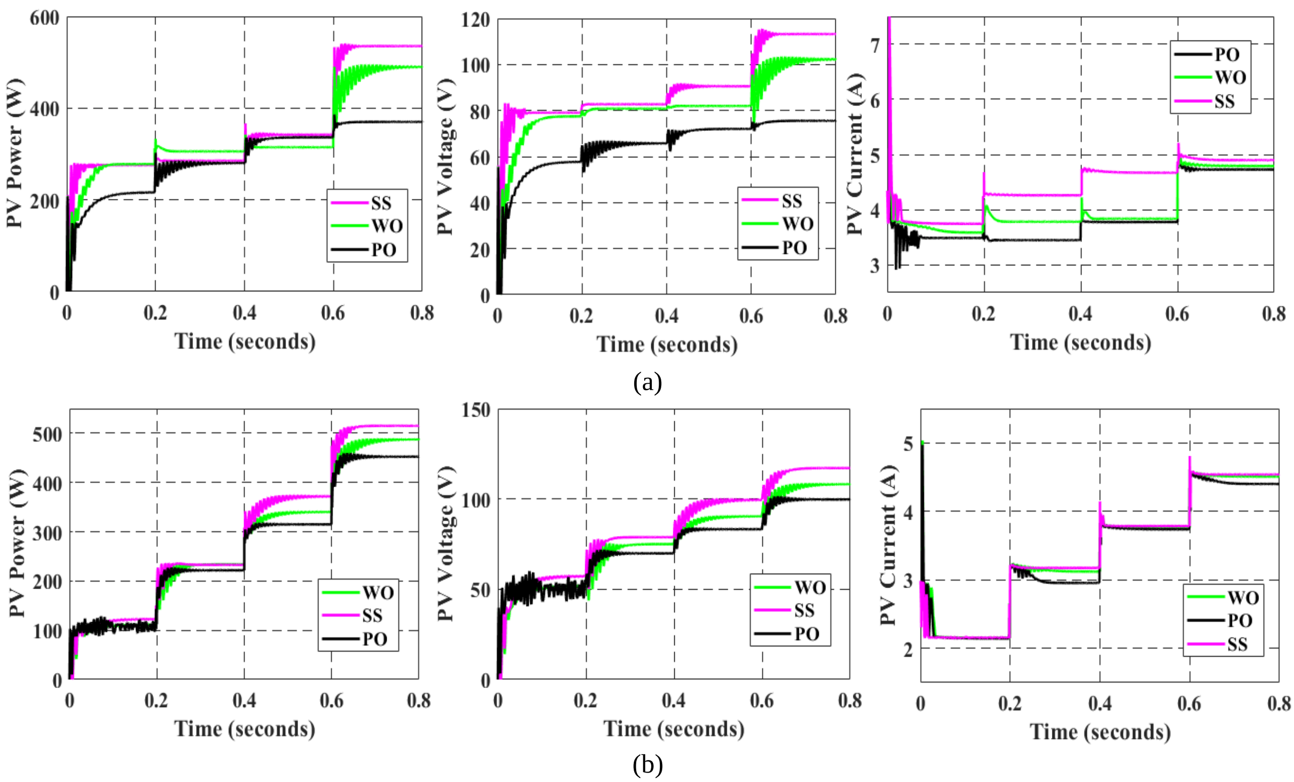


Figure 9. Tracking characteristics; (a) Rapid change in insolation, (b) Extreme change in insolation.

The comparison between SS, WO and PO is presented in Table 2 with regard to the tracking efficiency, and tracking speed with the different shading patterns. The features of the above-said algorithms are presented in Table 3. Figs. 10-11 show the characteristics of the PV power system with the different shading conditions. From the above discussions, it is witnessed that the SS algorithm locates the GP accurately during any change in operating conditions. The SS MPPT algorithm upshots in quicker convergence speed with the comparable efficiency. To conclude, the SS algorithm based MPPT technique is capable of flexible towards the various solar insolation conditions.

TABLE II. COMPARISON OF SS, WO AND PO MPPT METHODS

| Shading Conditions | MPPT | PV Power (W) | Tracking Time (Seconds) | $P_{max}$ from Curve (W) | Efficiency (%) |
|---|---|---|---|---|---|
| Pattern 1 | SS | 296.8 | 0.023 | 312 | 95.12 |
| | PO | 280.2 | 0.512 | | 89.81 |
| | WO | 305.1 | 0.084 | | 97.78 |
| Pattern 2 | SS | 345.8 | 0.052 | 352 | 98.23 |
| | PO | 326.3 | 0.059 | | 92.69 |
| | WO | 311.6 | 0.072 | | 88.51 |
| Pattern 3 | SS | 527.4 | 0.042 | 535 | 98.57 |
| | PO | 377.5 | 0.041 | | 70.56 |
| | WO | 499.4 | 0.502 | | 93.34 |

TABLE III. FEATURES OF VARIOUS MPPT TECHNIQUES

| MPPT | Regular Tuning | Response | Power Oscillation | GP Convergence | Complexity |
|---|---|---|---|---|---|
| SS | No | Fast and accurate | Less | Guaranteed | Easy |
| WO | No | Moderate and less accuracy | Moderate | Guaranteed | Medium |
| PO | Yes | Sluggish and poor accuracy | High | Not Guaranteed | Easy |

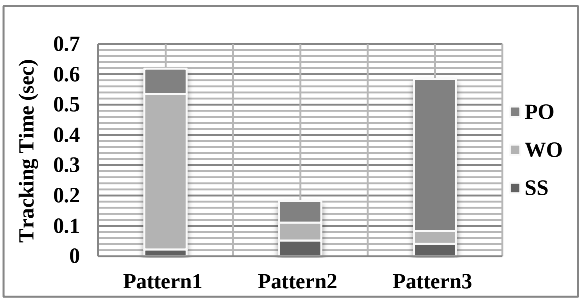


Figure 10. Convergence (Tracking) time of various MPPT techniques

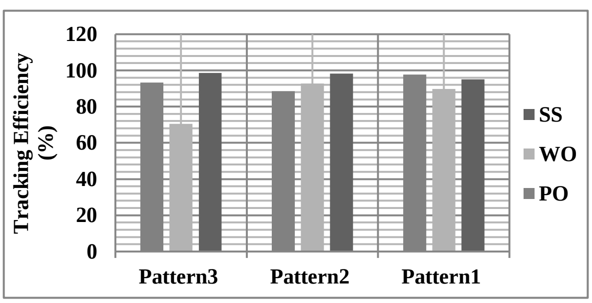


Figure 11. Tracking efficiency of various MPPT techniques

## 5. CONCLUSIONS

A novel SS algorithm based MPPT technique is presented in this paper to track the GP when the PV system is subjected to various shading conditions. The proposed SS algorithm is validated with 3S PV array configurations under different conditions such as a rapid insolation change, PSCs and an extreme insolation change. The PV systems displays multiple LP under these operating conditions, the SS algorithm locates the GP with great tracking efficiency, accuracy, and fast convergence speed. From the simulation results and further discussions, the SS based MPPT technique is superior in terms of tracking time and efficiency. The computation burden of the SS algorithm is eliminated by selecting lower search agents with less iteration. In this paper, the search agents and number of iterations are limited to 15 and 50 iterations for the simulation analysis. To conclude, the proposed SS algorithm has less standard deviation which allows the SS algorithm to locate the GP accurately and effectively.

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