Enhancing the Maximum Power Extraction in Partially Shaded PV Arrays Using Hybrid Salp Swarm Perturb and Observe Algorithm

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Abstract: Partial shading is a common problem faced by photovoltaic (PV) modules installed in residential areas. During shaded conditions, the power voltage (P-V) characteristics of the PV array consist of many local power peaks and a global power peak. Out of the many maximum power tracking algorithms, the perturb and observe (PO) is considered as the simplest algorithm. However, PO fails in tracking maximum power during shaded conditions, as it can track only a single power peak. In this proposed work, additional modification to PO algorithm is given by combining it to a metaheuristic Salp Swarm (SS) algorithm. Thus, a hybrid Salp Swarm Perturb and Observe (SSPO) algorithm is proposed in this paper, wherein the SS algorithm is used to locate the approximate global peak, and PO is utilized to find the exact global power. The proposed algorithm can track the exact power during uniform and partial shaded conditions. The SSPO is tested under steady state and dynamic conditions using MATLAB/Simulink. The obtained results are compared with the Salp swarm and conventional PO algorithm and it shows that SSPO can track the maximum power in all the conditions with 99 % efficiency and faster tracking time.

Keywords- Salp swarm algorithm; Partial shading; Maximum power point tracking, Perturb and observe algorithm, Stand alone PV system.

1. Introduction

The increase in global energy consumption and the adverse impact of the greenhouse effect forces the world to make use of renewable energy sources. As a result, global renewable energy capacity was increased to 2.4 GW in 2018. Out of many renewable energy sources, solar is considered as an essential source for the future because of the benefits such as low cost, less maintenance, and more importantly the global availability of sunlight. Another important reason for the popularity of solar is the areas such as deserts, hilly regions and difficult terrains, where power from the electric utility grid is impractical can be powered by solar PV system [1].

On the other hand, the power voltage (P-V) characteristics of the PV panel is nonlinear and it exhibits a single global power peak (GPP) under normal and stable irradiation condition. Hence, a maximum power point tracking (MPPT) controller is always equipped between the PV panel and load to extract the maximum available power from the PV. The MPPT controller is a combination of a DC/DC converter and an embedded controller. The embedded controller is loaded with MPPT algorithm and it operates the converter always at maximum power point region of the PV panel.

Numerous conventional MPPT algorithms are available for tracking the unique power peak efficiently such as incremental conductance (INC), perturb and observe (PO), curve fitting technique etc [2]-[3]. Commercially the PO algorithm is implemented in most of the MPPT controllers because of its simple steps and it produces less thermal stress on the converter switches [4].

The PV system installed in residential areas may not receive uniform irradiation all the time and it is often partially shadowed by the tree branches, nearby poles and bird droppings, etc.[5]. Under partially shaded condition, the output P-V characteristics of the array consist of multiple peaks and the current-voltage characteristics (I-V) consist of multiple steps. Conventional algorithms like PO, INC can track only single peak and it is not suitable for tracking under partial shading conditions.

Hence, to track the GPP under partially shaded condition, many control techniques from different domains have been introduced in the literature [6]. Some of the notable techniques are: fuzzy and neural network based tracking [7]-[10], thermography based MPPT [11], and many metaheuristics algorithm based controllers [12]. Among the control techniques, the metaheuristics based tracking is more prominent among the researchers because it is simple and has good tracking accuracy, does not require large training data as in machine learning and it can be easily implemented in low cost controllers.

Recently, many swarm intelligence (a group under metaheuristics) algorithms [13] were applied successfully in MPPT and their tracking results under partial shading conditions are very accurate. Some of them are flashing fireflies MPPT, bat search algorithm [14], moth flame optimization [15], human psychology algorithm [16], and so on. The exploration and exploitation mechanism estimates the performance of swarm intelligence techniques. During exploration, the search agents move globally in the search space to find possible solutions. Whereas during exploitation, the search agents search locally in the solutions obtained from the exploration phase. There is no proper procedure available to maintain the tradeoff between exploration and exploitation. Hence in most of the metaheuristics algorithms, the exploration and exploitation take place randomly and it takes more time to converge.

Many hybrid algorithms [17] were proposed in the literature wherein; two metaheuristic algorithms are combined in such a way to improve their overall exploration and exploitation capability. Some notable hybrid algorithms are Jaya optimization with DE (jayaDE) [18], artificial bee colony with particle swarm optimization (ABCPSO) [19] and fractional chaos with flower pollination (FCFPA) [20]. Although the tracking performance of the hybrid algorithms is good, the parameters of the algorithm will increase, the structure becomes complex and it needs an expensive controller for implementation.

To reduce the complexity and to implement in a low cost controller, some researchers proposed two stage algorithms wherein, a metaheuristic algorithm is combined with conventional single peak tracking algorithms. Some of the notable works are ant colony with PO [21], particle swarm optimization (PSO) with PO [22], genetic algorithm (GA) with PO [23] and whale optimization (WO) with PO [24], etc. In works [21],[22], the metaheuristics algorithm is first executed and after its convergence to the approximate GPP, PO is applied to find the exact GPP. To reduce the tracking time, in [23], [24] the metaheuristics algorithm is executed for a certain number of iterations and then PO is applied to find the GPP. In [23], [24]the exploration and exploitation are selected using random numbers and hence it may create oscillation at the initial stages. The oscillations may produce unwanted thermal stress on converter switches.

From the presented literature, the following shortcomings are identified:

- Due to inadequate exploration and exploitation, the algorithms create more oscillations at the output.
- Slow tracking speed.
- Difficult to implement due to complex calculations used in algorithms.

In this work, a novel Salp Swarm Perturb and Observe (SSPO) algorithm is proposed for tracking GPP under uniform and partially shaded conditions. The SSPO is a combination of recently introduced Salp swarm (SS) [25] and conventional PO algorithm. The SS algorithm can track the global value within a few iterations and the PO can track the unique power peak efficiently. Thus, in this work, the SS algorithm is used to find the approximate global peak and the PO is utilized to find the exact power in the peak. The exploration and exploitation in SS algorithm are uniformly maintained and hence oscillation is reduced during tracking. There are no complex calculations present in SSPO and hence easy to implement. A brief comparison between the proposed algorithm and the existing methodology is presented in Table 1.

The significant contributions of this work are:

1. A novel hybrid SSPO algorithm is introduced to track the maximum power under partially shaded condition.
2. The effects of the partially shaded condition are explained.
3. The efficiency of SSPO is validated under steady state (uniform and partial shading) condition and dynamic (sudden and dynamic irradiance change) condition through simulations.
4. The performance of SSPO is compared with SS and PO algorithm in terms of tracking time, efficiency and payback period.

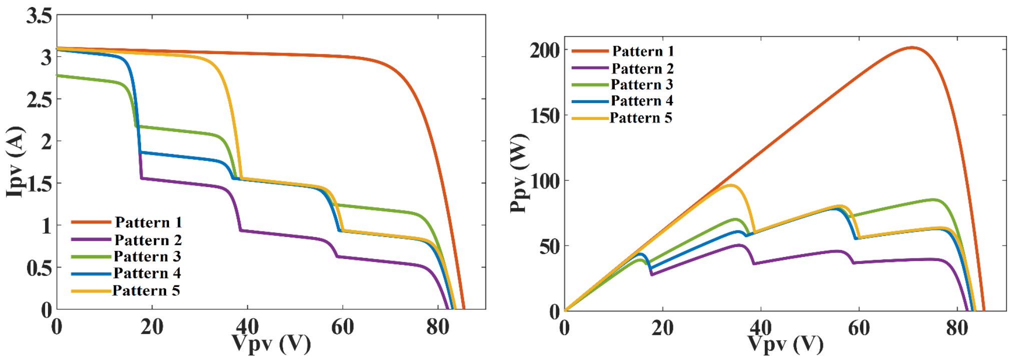
The rest of the paper is structured as follows: Section 2 describes partial shading effects. In Section 3, the proposed SSPO methodology is explained briefly. In Section 4, the results and discussions are presented. The efficiency and performance comparison is presented in Section 5. In Section 6, the conclusions are presented.

2. Partial Shading Effects:

The partial shading is a condition in which the PV panels receive uneven irradiation due to sitting of birds, dust, the shadow of nearby towers, etc.. In series connected panels the uneven irradiation may create hot spot problems. Hence bypass diodes are connected across each panel for protection. Contrarily, the use of bypass diodes creates different current at the PV terminals and this effect becomes more severe in large PV arrays. Figure 1 shows the output characteristics of a PV array with four panels connected in series. Under partial shaded condition, the I-V characteristics exhibit multiple steps and P-V characteristics consist of multiple peaks as shown in Fig. 1(a) and Fig. 1(b) respectively. Hence, an efficient maximum power tracking algorithm is

Table 1. Comparative analysis of different MPPT algorithms.

Ref	**Algorithm**	**Type**	**Complexity**	**Remarks**
[4]	PO	Conventional	Simple	Efficient but not suitable for partial shaded condition.
[10]	Machine learning	Artificial Intelligence	Complex	Superior tracking performance but not tested under dynamic conditions.
[11]	Thermography	Thermal Imaging	Complex	Thermal cameras are used to find the module fault and then the algorithm is used to find the global peaks.
[14]	BAT search	Bio Inspired (BI)	Medium	Tracking performance is good, but proper tuning of initialization parameters is required
[16]	Human Psychology		Medium	The algorithm uses only a single current sensor for tracking the global peak and shows good tracking performance.
[18]	jayaDE	Hybrid BI + BI	Complex	Accurate tracking of the global peak is possible. Proper tuning of initial parameters is required.
[19]	ABCPSO		Complex	The algorithm shows good performance under a steady partial shaded condition but not tested under dynamic conditions.
[20]	FCFPA		Complex	Fractional chaos is combined with FPA for fast tracking of global peak and shows good dynamic tracking performance.
[21]	ANT PO	Hybrid BI + Conventional	Medium	Accurate tracking of the global peak is possible, but it takes more time to converge.
[22]	PSO PO		Medium	Good tracking performance. Inadequate exploration of PSO leads to slow tracking speed.
[23]	GA PO		Complex	GA is used to find global peak, and PO is implemented to track the exact peak. Performance is good, but the control structure is complex.
[24]	WO PO		Medium	The exploration and exploitation of WO algorithm are selected using random numbers and hence convergence towards local power also possible.
Proposed SSPO			Medium	The SSPO algorithm is simple and has good exploration and exploitation. Easy to implement in a low cost controller due to less parameter initialization.



(a) (b)

Figure 1: Simulated curves: a) I-V characteristics, b) P-V characteristics

required for tracking under partial shaded conditions. The algorithm proposed in this work can track the maximum power efficiently under these complex shaded conditions.

3. Hybrid Salp Swarm Perturb and Observe (SSPO) Method:

3.1 The proposed methodology:

In the maximum power tracking technique, the MPPT controller tracks the maximum power by adjusting the duty cycle of the converter. In the SS algorithm, the maximum power position in P-V curve can be selected as food position and the duty cycles can be chosen as searching salps. The duty cycle with maximum power is considered as leader and the remaining duty cycles are followers. The objective function can be formulated as shown in Equation (1):

$$f\left(D\right)=MaxP_{PV}\left(D\right) \qquad (1)$$

constraint $D_{min} \leq \mathrm{D} \leq D_{max}$

where Max P_{pv} is maximum available PV power at duty cycle D. D_{min} and D_{max} are minimum and maximum duty cycles and are selected as 10 %and 90 % respectively.

The possibilities of reaching the global value in four iterations are explained below:

1. Generally for any metaheuristic algorithm, the initial position of search agents are declared either randomly or in fixed positions. The random initialization increases the convergence time and sometimes it may wrongly converge to the local value. Whereas if the algorithm is initialized with known values that are close to the possible solutions, then the convergence towards global value within a few iterations is highly possible.

2. For a single unshaded module, the maximum peak power (P_{MPP}) occurs approximately at 80% of V_{oc} of the module. If the panels are connected in series and under the partially shaded condition the output curve can have multiple peaks. As explained in [26], the peaks are placed at 80% V_{oc} of the module and the displacement between successive peaks is approximately 80% of V_{oc} of the module. Hence if the duty cycles are initialized in the search space with equal distance between D_{min} and D_{max} then there are chances that at least one search agent is nearer to the global peak.

For better understanding, the proposed methodology is illustrated in Fig. 2. In this work, the duty cycles are initialized between D_{min} (0.1) and D_{max} (0.9) at equal distance. Figure 2 shows the simulated results of power, voltage and the position of power on the P-V curve after the first iteration. It can be seen that the power obtained by all the duty cycles is nearer to the power peaks (global and local) and the power obtained by the 4[th] duty cycle is closer to the approximate global peak. The SS algorithm utilized in this paper can uniformly maintain the exploration and exploitation and hence during initial stages, it explores more and in the final stages, it exhibits deep exploitation. As a result, faster convergence with fewer oscillations can be obtained. Hence after 4 iterations, the duty cycles are converged nearer to the global value and if the PO is initiated from the best duty cycle then the exact global power can be reached.

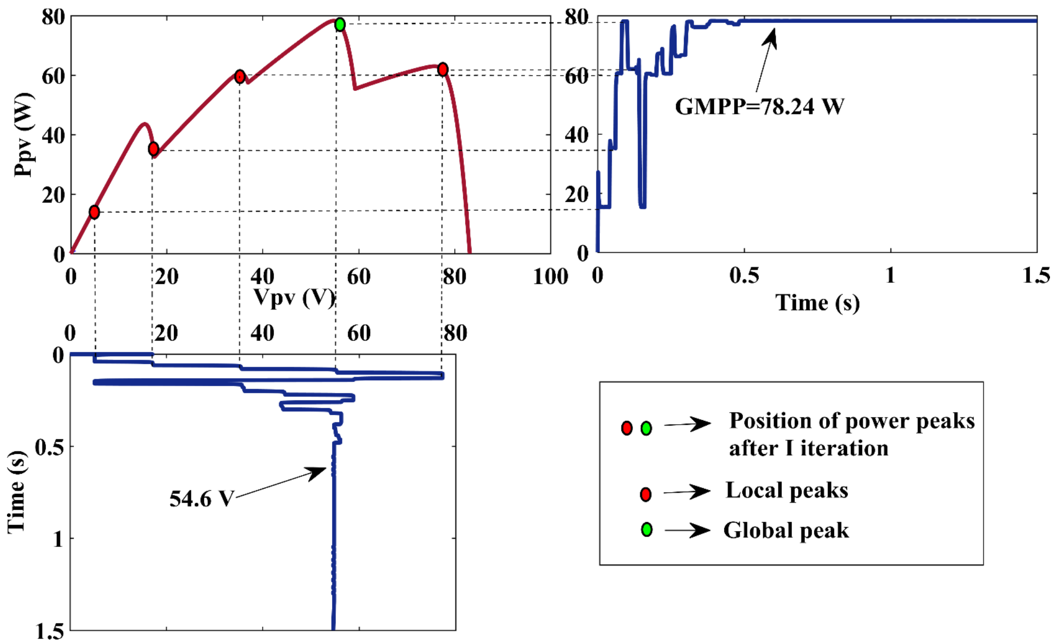


Figure 2. Illustration of the proposed methodology.

3.2. Salp Swarm (SS) optimization algorithm:

The SS optimization algorithm is a recent metaheuristic technique proposed by Mirjalili et.al [25] for solving single and multiple objective optimization problems. The SS optimization is based on the foraging behaviour of under ocean creatures called salps. They have a transparent barrel shaped body and moves in the ocean by pumping the water through it. They attach and form groups called salp chains. The leader salp presents at the front of the chain and the followers are attached to it. Mathematically the searching behaviour of salps can be modelled [25] as follows: -

The position of the leader salp is updated using Equation (2)

$$x_j^1 = \begin{cases} F_j + c_1((ub_j - lb_j)c_2 + lb_j)c_3 \geq 0.5 \\ F_j - c_1((ub_j - lb_j)c_2 + lb_j)c_3 < 0.5 \end{cases} \quad (2)$$

Where x_j^1 is the position of leader salp in j^{th} dimension, F_j is the position of food source in j^{th} dimension, ub_j and lb_j are upper and lower bound of j^{th} dimension respectively. c_2 and c_3 are random numbers uniformly generated between 0 and 1.

The parameter c1 controls the exploration and exploitation mechanism and it is expressed in Equation (3) as follows:

$$c_1 = 2e^{-\left(\frac{4l}{L}\right)^2} \quad (3)$$

Where the parameter l is the current iteration and L is the maximum number of iterations.

The followers update their position using Equation (4)

$$x_j^i = \frac{1}{2}\left(x_j^i + x_j^{i-1}\right) \quad (4)$$

Where $i \geq 2$ and x_j^1 is position of j^{th} follower in j^{th} dimension.

3.3. Steps followed in hybrid SSPO for MPPT application:

The flowchart for the proposed SSPO algorithm is presented in Fig. 3 and the explanations for the steps are given below:

STEP 1: The algorithm parameters are initialized: maximum no. of iteration is 4, step size (PO) is 0.001, No. of duty cycles are 5 and they are evenly distributed between D_{min} (0.1) and D_{max} (0.9).

STEP 2: The duty cycles are applied sequentially to the converter for every 30 ms and the corresponding PV power is calculated. The duty cycle with maximum power is deployed as global best (leader salp) and the remaining values are selected as followers.

STEP 3: The duty cycles (leader and followers) are updated using Equation (2) and Equation (4).

STEP 4: STEP 2 and 3 are repeated up to 4 iterations. If the iteration is greater than 4 then PO is executed. The initial duty cycle ($D_{initial}$) for PO algorithm is selected from the global duty cycle (D_{leader}) obtained from the SS algorithm.

STEP 5: To identify the irradiance change and to reinitialize the algorithm, Equation (5) is deployed

$$\frac{\left|P_{PV}(i) - P_{PV}(i-1)\right|}{P_{PV}(i)} > 0.2 \quad (5)$$

Where i is the iteration number $P_{PV}(i)$ and $P_{PV}(i-1)$ are the power obtained during current and previous iteration respectively.

4. Results and Discussions:

The performance of the proposed algorithm has been verified using MATLAB R2016b software, intel core i5 processor with 8 GB memory. The complete block diagram of the test system used for simulation consists of 4 series connected panels, a boost converter and a resistive load as shown in Fig. 4. The PV array is modelled in Simulink [27] and the parameters are presented in Table 2. The boost converter parameters are presented in Table 3. The MPPT algorithms are coded using an embedded MATLAB function block of MATLAB. For partially shaded condition the panels should receive uneven irradiance values and hence five different shading patterns are created and the irradiance profile is given Table 4. Despite of any shading pattern, the number of local peaks in a PV array is equal to the number of series connected panels. The position of global peaks may change to any location based on the shading pattern and it cannot be predicted. However, the algorithm should track the exact peak irrespective of its position. Hence, the irradiance values in Table 4 are selected in such a way that the global peak occurs at all the 4 positions. The temperature is maintained constant at 25°C throughout the experiment. To maintain fairness in comparison the algorithms SSPO and SS are initialized with the same duty cycle values. The parameters of algorithms used in the simulation are tabulated in Table 5. The algorithms are tested and compared under steady state condition (uniform and partial shading) and dynamic conditions (sudden change in irradiance and dynamic change in irradiance).

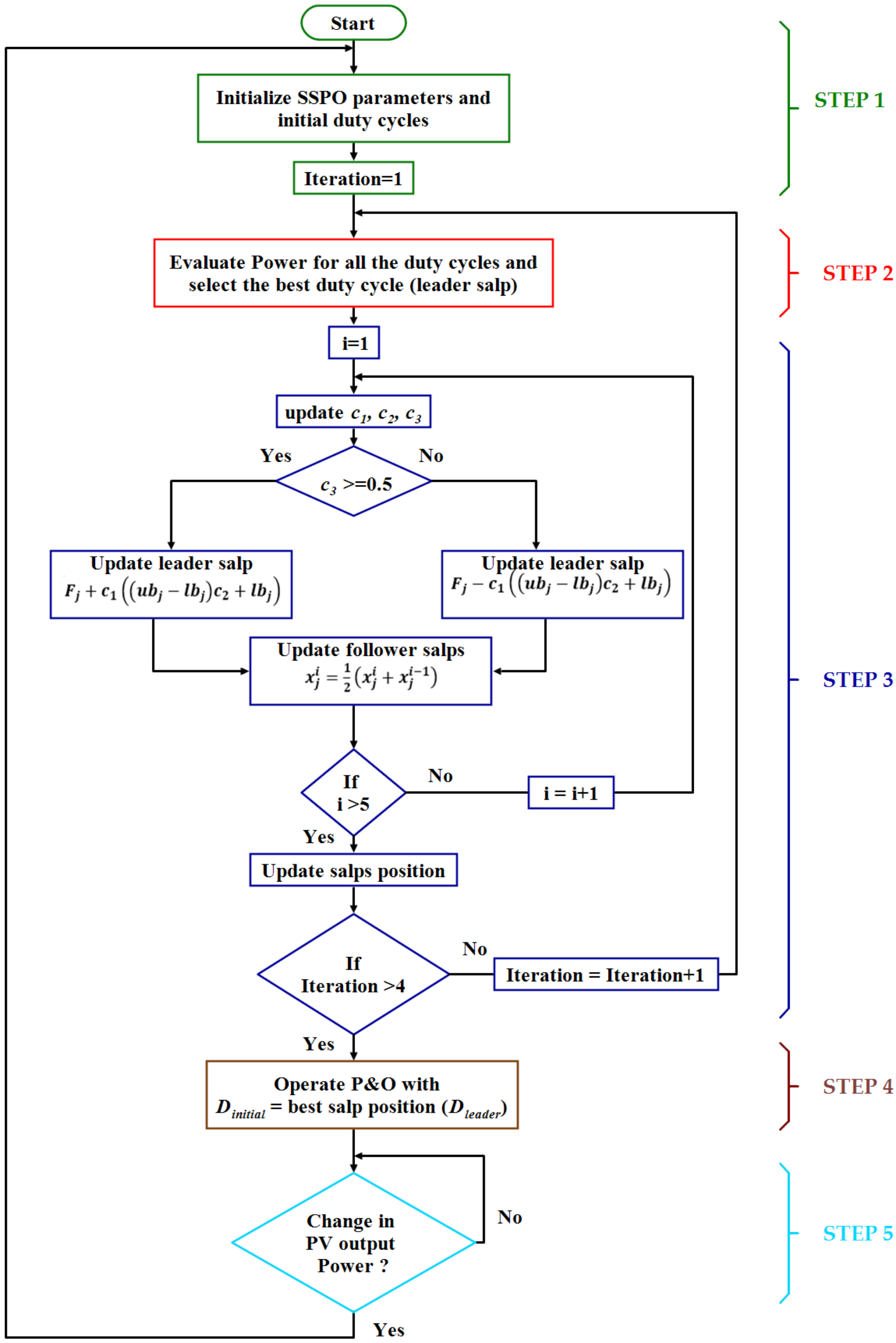


Figure 3. Flowchart of proposed hybrid SSPO algorithm

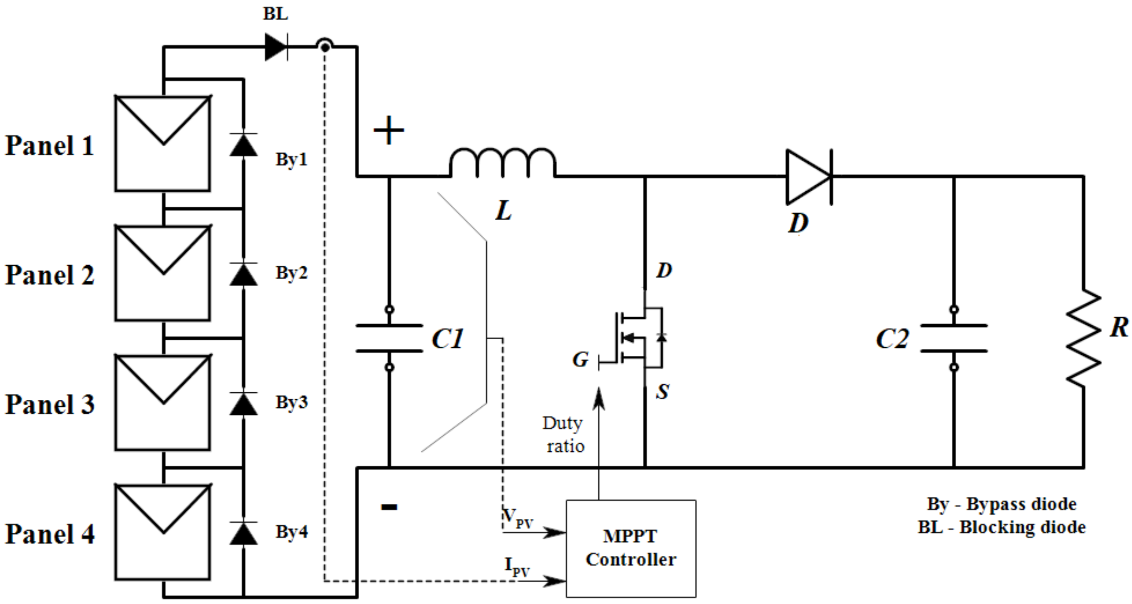


Figure 4. Block diagram of the complete test system

Table 2. Parameters of the single 50 W PV module (at 1000 W/m^2 and 25˚C)

Parameter	Value
Maximum rated power (P_{MPP})	50 W
Voltage at maximum power (V_{MPP})	17.7 V
Current at maximum power (I_{MPP})	2.85 A
Open circuit voltage (V_{OC})	21.4 V
Short circuit current (I_{SC})	3.1 A
PV cell Type	Polycrystalline
No. of cells in series	36

Table 3. Parameters of Boost Converter

Parameters	Value
Input Capacitor (*C1*)	10µF
Output Capacitor (*C2*)	50µF
Inductor (*L*)	10mH
Resistor (*R*)	120Ω
Switching Frequency (*fs*)	25kHz

Table 4. Irradiance pattern for the PV array

Pattern	Irradiance in (W/m^2) at 25ºC				Local peaks	Position of Global peak
	Panel 1	Panel 2	Panel 3	Panel 4		
1	1000	1000	1000	1000	0	1
2	1000	300	500	200	3	2
3	400	500	700	900	3	4
4	300	500	600	1000	3	3
5	300	1000	500	1000	2	1

Table 5. Parameters of algorithms used for simulation

Parameters	SSPO	SSO	PO
Initial Salp count	5	5	-
Maximum iterations	4	10	-
Sample time	30ms	30ms	30ms
Step size	0.001 (for PO)	-	0.001

4.1. Steady State Conditions

4.1.1. Uniform Irradiation

For testing the panels under uniform irradiation condition, all the 4 PV panels are treated with the same irradiance value of 1000 W/m^2. The theoretical maximum peak power and voltage obtained under this condition are 201.4 W and 70.82 V respectively as shown in Fig. 5(a). The SSPO and SS tracked the exact power (201.4 W) at 0.52 s and 1.24 s respectively as shown in Fig. 5(b) and Fig. 5(c). Whereas PO algorithm has tracked 201.2 W at 0.78 s as in Fig. 5(d). The results show that under unique peak condition all the three algorithms (SSPO, SS and PO) can perform well and the proposed SSPO algorithm can track faster than others.

4.1.2. Partially Shaded Condition

To test the algorithms under partial shaded condition, the panels are provided with shading pattern 4 as in Table 4. Pattern 4 is selected to show the difference in tracking by PO (local peak) and SSPO (global peak) under partially shaded condition. The panels (1 to 4) receives irradiance of (300,500,600,1000)W/m^2 respectively. Figure 6(a) represents the P-V characteristics for pattern 4 and it consists of a global peak (78.26 W) at third position and three local peaks with power value 43.52 W, 60.63 W and 62.95 W at first, second and fourth position respectively. Figure 6(b) and (c) illustrate the tracking results of SSPO and SS algorithm respectively, where the SSPO can track the global peak (78.2 W) at 0.54 s and SS tracks the power at 1.10 s. Since the PO algorithm is a single peak searching algorithm, it is converged at the local peak (62.9 W) itself as shown in Fig. 6(d). The power tracked by PO algorithm is 15 W lesser than the available global power and it shows inaccurate tracking of PO under partially shaded condition. When compared with SS and PO algorithms, the SSPO tracks the global power with fewer oscillations and less tracking time.

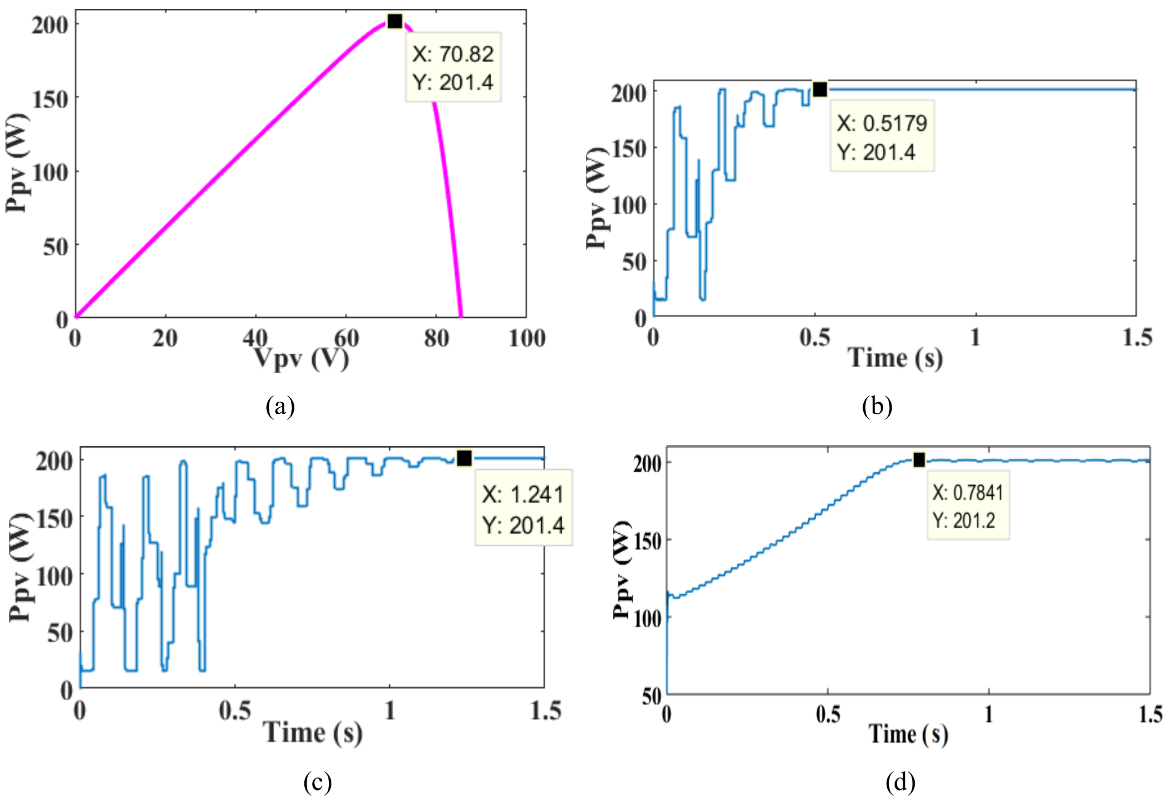


Figure 5. Simulated power waveforms: a) P-V characteristics at 1000 W/ m^2, b) SSPO, c) SS, d)PO.

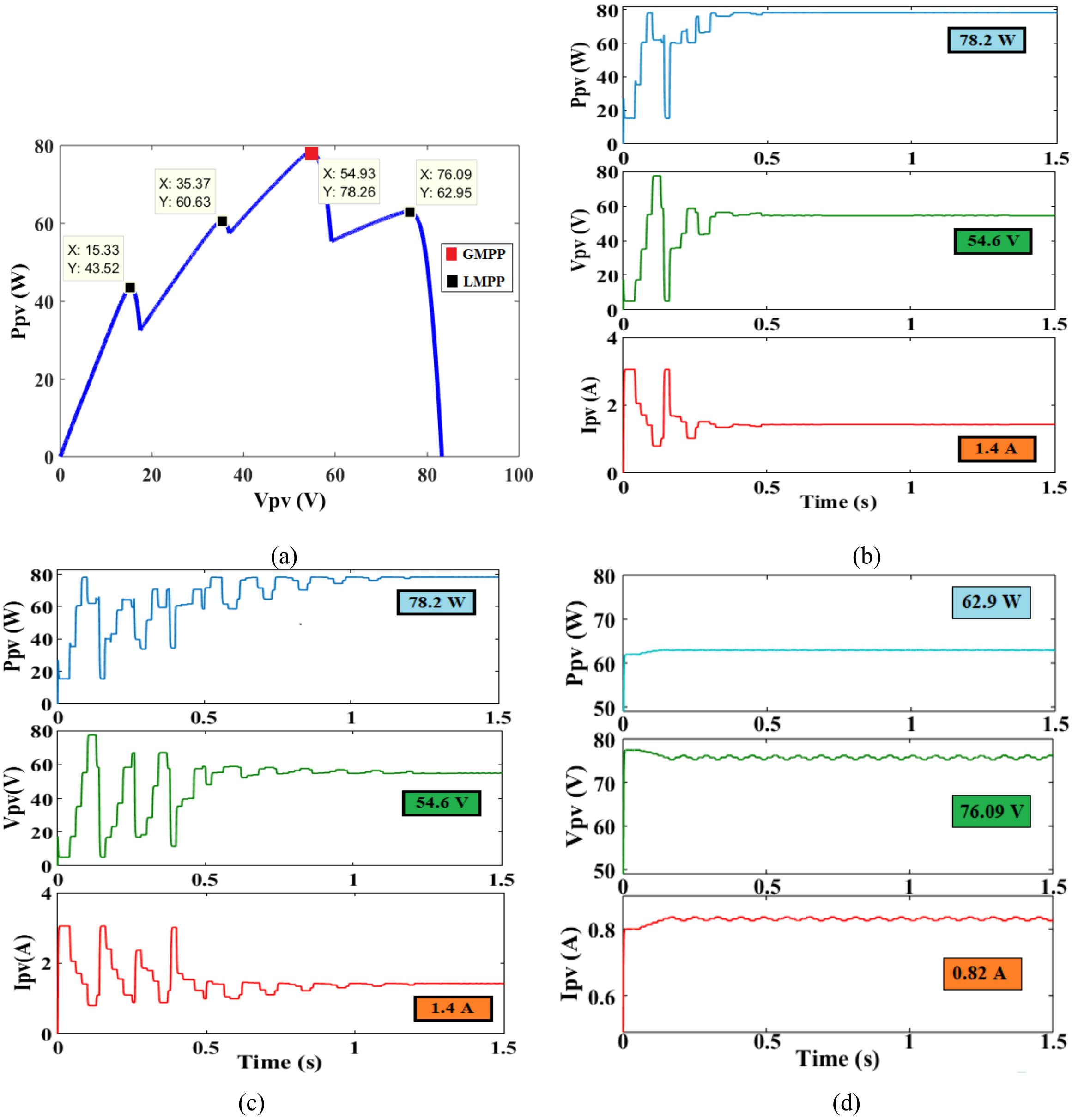


Figure 6: Simulation results under partially shaded condition: a) P-V characteristics for pattern 4, b) SSPO, c) SS, d) PO.

4.2. Dynamic Conditions

4.2.1. Sudden Change in Irradiance

The sudden change in irradiance condition practically occurs in a PV system when there is a fast movement of clouds, swaying of trees and flying of birds appears over the panel. To emulate this effect in simulation, a step change in irradiance from 500 W/ m^2 to 1000 W/ m^2 is used. The P-V characteristics for a step change in irradiance are shown in Fig. 7(a) which shows the maximum power for 500 W/ m^2 and 1000 W/ m^2 as 96.3 W and 201.4 W respectively. For SSPO and PO algorithm the step change in irradiance is given at 0.7 s and for SS algorithm it is given at 1.5 s. The SSPO algorithm tracks the maximum power 201.4 W at 0.55 s and 96.3 W at 1.25 s as shown in Fig. 7(b). To find the final convergence value, the simulation time for SS algorithm is extended to 3 s as shown in Fig. 7(c) and the maximum power 201.4 W is tracked at 1.3 s and 96.3 W at 2.6 s. Whereas the PO tracks the maximum power of 201.4 W at 0.7 s and 96.29 W at 1.28 s. From the results shown in Fig. 7(b) to 7(d), it can be seen that the power tracked by algorithms (SSPO, SS, PO) under the sudden change in irradiance is effective but the proposed SSPO only achieves tracking with lesser time.

4.2.2. Dynamic Change in Irradiance

To further test the algorithm with complex environmental conditions the dynamic change in irradiance test has been done. Hence, the PV panels are initially treated with low irradiance of 300 W/ m^2 (for 0s to 0.7s) and then irradiance pattern 4 from Table 4 has been introduced for 0.7s to 1.5s. The P-V characteristics of this condition is illustrated in Fig. 8(a) and it shows that for the irradiance of 300 W/ m^2 the maximum power is 54.1 W and for pattern 4 the global peak is available at 78.26 W. The SSPO tracks the exact power of 54.1 W at 0.54 s and 78.2W at 1.24 s and it is shown in Fig. 8 (b). The SS algorithm tracks 54.1 W at 0.88s and 77.32 W at 2.6s as shown in Fig. 8(c) and it can be noticed that, when pattern 4 is executed the SS algorithm converges to 77.32W and it is lesser than the global power value. When PO is executed under this condition, for 300 W/ m^2 it tracks 54.1 W at 0.3 s and when pattern 4 is executed it tracks 62.9 W at 0.75 s as shown in Fig. 8(d). When compared with SS and PO algorithms, the performance of the SSPO algorithm is good in terms of tracking exact power with lesser time.

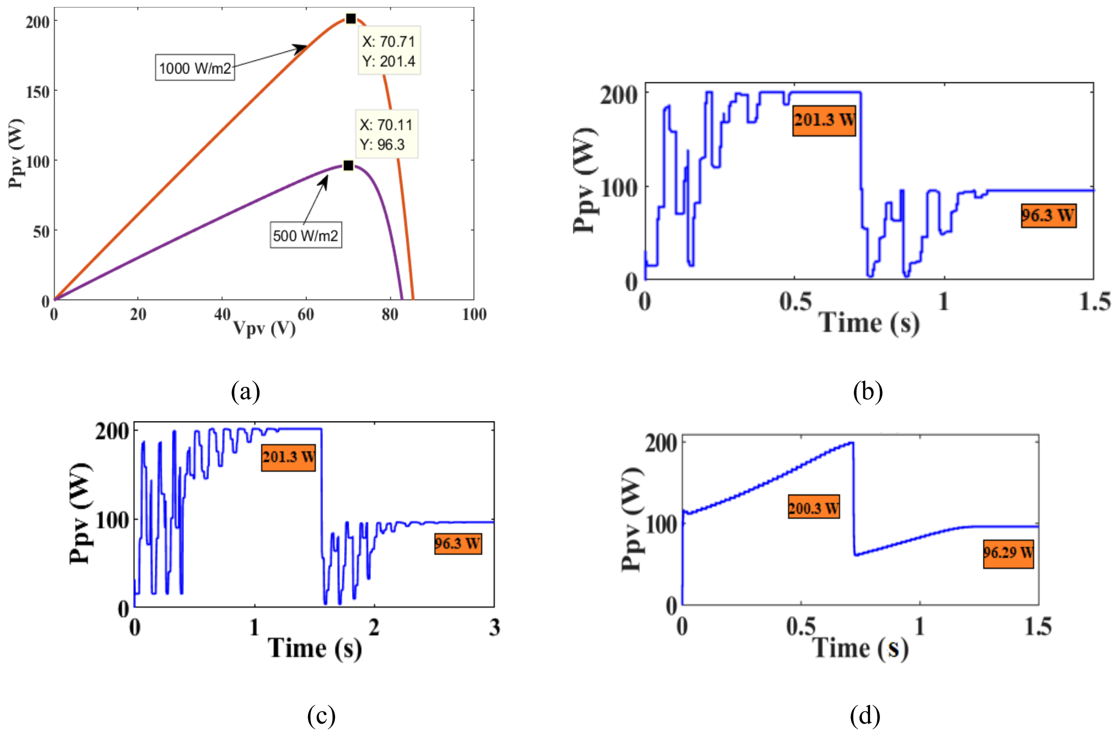


Figure 7: Sudden change in irradiance results: a) P-V characteristics for 500W/ m^2 and 1000 W/ m^2,b) SSPO, c)SS, d)PO.

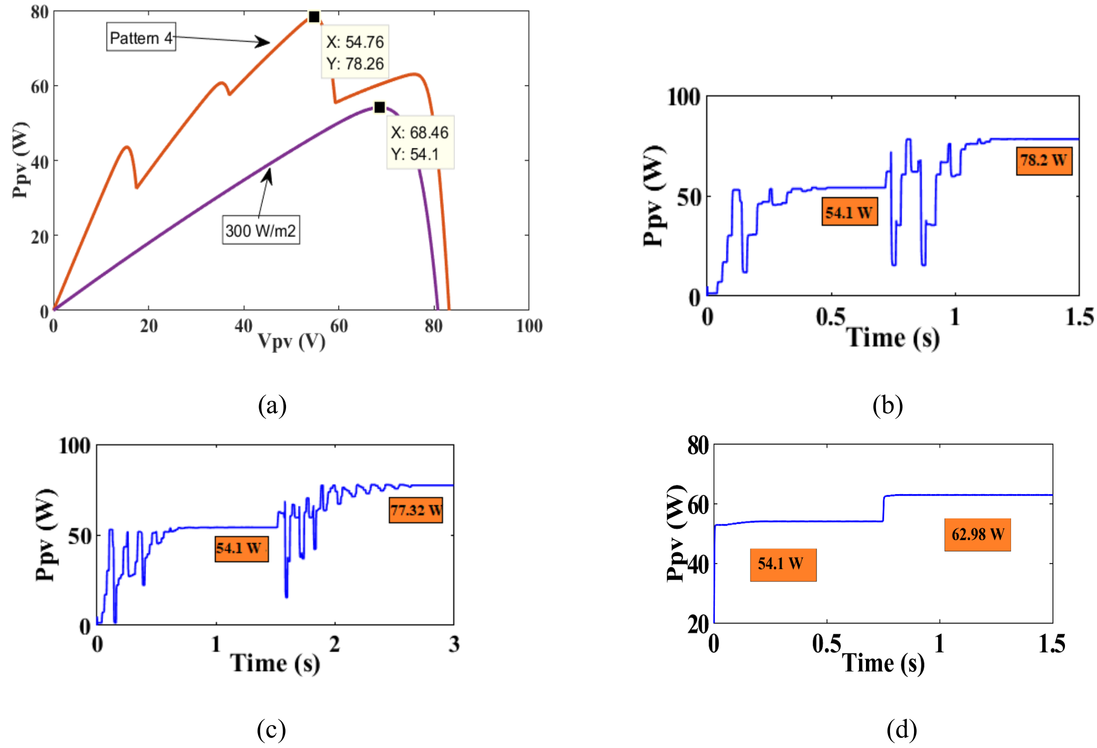


Figure 8. Dynamic change in irradiance results: a) P-V characteristics for 300 W/ m^2 and pattern 4, b) SSPO, c) SS, d)PO.

5. Efficiency and Performance Comparison

In this section, the simulated results are compared and discussed under the following criterion: Maximum power tracking efficiency and tracking time, payback period and algorithm complexity.

5.1 Maximum power tracking efficiency and tracking time:

The performance of the proposed SSPO algorithm under steady state and the dynamic condition has been analysed in sections 4.1 and 4.2 and the results show that the proposed SSPO is efficient in tracking maximum power in all conditions. However, to further test the performance of algorithms under different global peak positions, they are simulated with the shading patterns given in Table 4 and the results are tabulated in Table 6. For better understanding, the results of efficiency and tracking time for the five cases are averaged and plotted as shown in Fig. 9. The average tracking efficiency in Fig. 9(a) indicates that the SSPO algorithm convergence towards global power is greater than 99%. The tracking time comparison in Fig. 9(b) shows that the average time taken by PO is 0.48 s which is much lesser, but in many shading patterns (2,4,5) it has reached the local power peaks. Whereas, the average tracking time of SSPO is 0.542 s which is lesser and also it has tracked the maximum power in all the shading patterns.

5.2 Comparison of payback period:

The algorithms have been compared in the economic point of view and are shown in Table 6. A simple payback period calculation has been done based on the results obtained by the three algorithms. The following assumptions are considered for the payback period calculation:

1. The test system considered in this paper has four series connected panels of 50 W each. A single 50 W panel costs ₹2500 [28] and therefore for 200 W (4 panels) the price is ₹10,000. Hence, the total payback amount considered is ₹10,000.

2. The solar power generation at the VIT Chennai campus laboratory (12.8406° N, 80.1534° E) is estimated as 9 hours (8 A.M to 5 P.M). Hence the units generated per day is calculated for 9 hours.

3. In our calculation, an electricity tariff charge of ₹ 3 per kW-hr is considered.

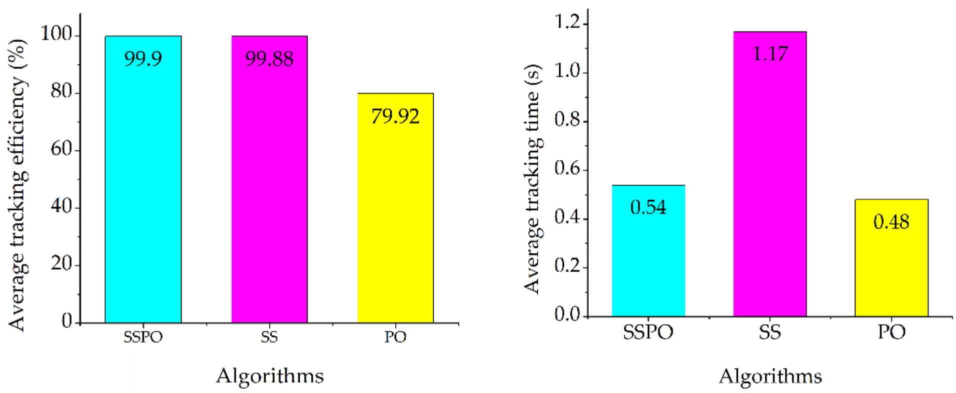
4. In this calculation, the PV panel retail cost alone is considered and the balance of materials such as installation charges, additional component costs, etc. are not considered.

The payback period calculation in Table 6 shows that the proposed SSPO shows less payback time than PO algorithm. For pattern 1 and pattern 3, the SSPO and PO algorithms show equal payback period because the pattern 1 consist of a unique peak and in pattern 3 maximum peak is present in the right position. Hence the PO can track the maximum power quickly and the payback period is also less.

5.3 Algorithm complexity:

The PO algorithm is simple and it can be installed in a low cost controller. However, during partially shaded condition it is not suitable as it may cause power loss. Whereas the structure of SSPO algorithm is very simple, free from complex functions and less parameter initialization. Hence the proposed SSPO can be easily implemented in a low cost embedded controller.

The analysis presented in section 4 and the discussions presented in this section shows that the proposed SSPO is suitable for enhanced peak power tracking in a partially shaded PV system.



(a) (b)

Figure 9. Comparison of algorithm tracking results: a)Average efficiency, b)Average time.

Table 6. Simulation result comparison for five different shading patterns

Pattern	GMPP (W)	Algorithm	Tracked GMPP results				Efficiency (%)	Units generated per day (kW-hr)	Units generated per month (kW-hr)	Total Income per month (₹). (₹. 3 / kW-hr)	Payback period for 200W panel (Years)
			Power (W)	Voltage (V)	Current (A)	Tracking time (s)					
1	201.4	SSPO	201.4	70.4	2.9	0.53	100.0	1.8	54.4	163.1	5.1
		SS	201.4	70.4	2.9	1.24	100.0	1.8	54.4	163.1	5.1
		PO	201.2	70.8	2.8	0.78	99.9	1.8	54.3	163.0	5.1
2	50.35	SSPO	50.3	35.5	1.4	0.52	99.9	0.5	13.6	40.7	20.5
		SS	50.3	35.5	1.4	1.40	99.9	0.5	13.6	40.7	20.5
		PO	39.4	74.2	0.5	0.30	78.2	0.4	10.6	31.9	26.1
3	85.17	SSPO	85.1	75.2	1.2	0.55	99.9	0.8	23.0	68.9	12.1
		SS	85	75.1	1.1	1.20	99.8	0.8	23.0	68.9	12.1
		PO	85.02	74.8	1.1	0.72	99.8	0.8	23.0	68.9	12.1
4	78.26	SSPO	78.2	54.6	1.4	0.54	99.9	0.7	21.1	63.3	13.2
		SS	78.2	54.6	1.4	1.10	99.9	0.7	21.1	63.3	13.2
		PO	62.9	76.09	0.82	0.20	80.37	0.5	16.9	50.9	16.3
5	96.2	SSPO	96.1	34.2	2.8	0.57	99.8	0.9	25.9	77.8	10.7
		SS	96	33.9	2.7	0.90	99.8	0.9	25.9	77.8	10.7
		PO	63.6	76.5	0.8	0.40	66.1	0.6	17.2	51.5	16.2

6. Conclusions

In this work, a novel hybrid SSPO algorithm is proposed for maximum power tracking under partially shaded condition. The simulation results show that the tracking efficiency under partially shaded condition is greater than 99%. In both steady state and dynamic conditions, the SSPO outperforms than SS and PO algorithm. The exploration and exploitation is uniformly maintained and hence the oscillations are significantly reduced at the initial stages of tracking. The less parameter initialization in the proposed algorithm makes it easier to implement in low cost hardware. The future work will be the development of hardware prototype for the proposed algorithm and testing with real PV panels.

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