A Selective Power Point Tracking Algorithm for Reduced Power Tracking in PV System

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Abstract- The integration of photovoltaic (PV) systems with microgrid and hybrid power systems is increasing nowadays due to its continuous power production in the daytime. However, when the load demand is less, the maximum power produced by the PV can overload the connected system. In this work, a selective power point (SPPT) tracking technique is proposed for tracking reduced power from PV. Additionally, the SPPT algorithm is combined with salp swarm perturb and observe method (SSPO) to track the maximum power whenever needed. The proposed algorithm works in two modes and are global mode and local mode. During global mode, SSPO is executed for tracking the maximum power and in the local mode SPPT algorithm is used for tracking the reduced power from PV. The performance of the proposed algorithm is validated under three different complex irradiation patterns using MATLAB simulations. The results show that the tracking efficiency is greater than 98%, and the tracking time is less than 1s under global and local modes.

Keywords Reduced power point tracking, salp swarm algorithm, partial shading, maximum power point tracking, Photovoltaic sytsem.

1. Introduction

Due to the government policies and the awareness on reducing the greenhouse effect, the use of renewable sources for power generation is increasing. Among the renewables, solar PV is preferred by everyone due to the abundance availability of sunlight and maintenance free operation. The PV panel's power voltage (P-V) characteristics are highly nonlinear and severely affected by irradiation and temperature variations. During uniform irradiation conditions, the P-V characteristics consist of a single peak, whereas during partial shaded conditions, it consists of multiple power peaks with one global peak [1]-[3]. The maximum power is delivered to the load only when the global peak region is tracked by the maximum power point tracking (MPPT). There are many MPPT algorithms proposed in the literature to track the maximum global peak. Some of the recent algorithms are bayesian network-based tracking [4], fuzzy control [5]-[6], ant colony optimization [7], modified firefly [8], human psychology optimization [9], harris hawk optimization [10], whale optimization differential evolution (WODE) [11], whale optimization perturb and observe [12], grey wolf perturb and observe [13] etc. These algorithms show good tracking performance under uniform and partially shaded conditions in a standalone PV system.

Nowadays, most of the PV system controllers are available with MPPT and grid integration capability. A block diagram of two stage PV grid connection is presented in Fig. 1. Hence, in the future, the possibility of connecting more PV panels in to the grid is very high. Though large PV integration supports the grid, the following PV related problems occur

- If the power demand is less and if the PV is operated at MPP region then grid overloading may occur.
- During cloudy weather, the irradiation varies, and hence the PV power generation fluctuates and further, it creates grid voltage fluctuations.

To overcome the above said issues, many countries revising and updating their grid codes [14] and suggesting active power control in PV systems. This aids in generating power from PV and also provides grid support when needed. Hence, operating PV always at the MPP region is not required.

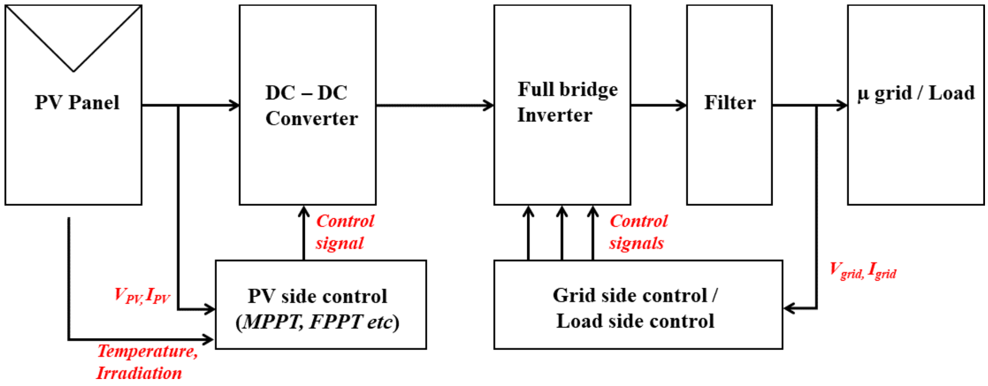


Fig. 1. Two stage grid connected PV system

Recently, researchers effectively handled this active power control issue from PV and suggested a new control technique called flexible power point control (FPPT). The FPPT works in either the left or right-side region of the PV curve and delivers the reduced power to the grid [15]. Some of the FPPT algorithms are discussed in this section. In [16], a constant power generation control for single stage and dual stage PV grid connection system is presented. The algorithm is used to generate PV voltage reference for constant PV power generation. The main advantage of this algorithm is, the PV power can be tracked on the left and right side of the power voltage (P-V) curve effectively.

In [17], a reduced power mode control is suggested, wherein a new algorithm is used to generate the reference power in order to reduce the power generation from PV. The proposed algorithm works on the right side (between maximum PV voltage (V_{mpp}) and open circuit voltage (V_{oc})) of the P-V curve in order to reduce the voltage oscillations at the DC link.

A new intermediate power point tracking method is proposed in [18]. This algorithm works in two modes, partial shading mode and limited power generation mode. During partial shading mode, PSO algorithm is used to track the maximum, whereas, during limited power mode, an intermediate power tracing controller is used to track the et power limit. It works on both the left and right side of the P-V curve. The only drawback is that during PSO operation, the oscillations and the settling time is more.

Recently, a secant method based FPPT is proposed in [19]. The algorithm is very simple and it can identify the environmental changes using the power reference. The steady state oscillation during tracking is less. The problems with partial shading conditions are not studied.

A binary search based FPPT is proposed in [20]. The voltage reference is calculated using binary search algorithm. The algorithm can detect voltage variations and irradiation change effectively. The oscillation around the steady state is significantly less.

To further support the research community in the area of FPPT technique, a selective power point technique (SPPT) is introduced in this work. Additionally, to track under partial shaded conditions it is combined with SSPO as SSPO – SPPT algorithm and a new searching methodology is proposed.

The significant contributions of the proposed work are:

- It can track the MPPT and reduced power simultaneously.
- It can work under any irradiation conditions, including partially shaded conditions.
- It always works in the P-V curve's right side (between V_{mpp} and V_{oc}) to reduce voltage oscillations.
- It can be able to maintain high voltage and low current at the output.
- The algorithm consists of simple steps and it is easy to implement in real time.

The remaining sections are organised as follows: In Section 2, the working of the proposed algorithm is explained in detail. Simulation and results are presented in Section 3. In Section 4, the comparative analysis of results is presented and in Section 5 conclusion is presented.

2. Working Operation of Proposed SSPO – SPPT Algorithm

The working operation of the proposed SSPO – SPPT technique can be explained with the help of Fig. 2. The P-V characteristics consist of two regions (left of MPP and right of MPP) other than MPP region as shown in Fig. 2(a). The power on the right side is mentioned as a, b, c and the left side powers are mentioned as a', b', and c'. It can be seen that the power at points (a and a') are identical but their voltages are different and the same thing can be observed at points (b, b' and c, c'). Also, the voltage difference on the left side of the MPP is higher than the right side of the MPP. Similarly, in Fig. 2(b), the current variation is higher on the right side of the MPP than on the left side.

The main aim of the proposed SPPT algorithm is to maintain high voltage and low current at the output. In this work, it is achieved by operating the converter at the right side of the MPP region of the P-V curve and it is highlighted as SPPT region in Fig. 2. The proposed technique's main advantages are that it creates less voltage oscillations, does not contain complex calculations, and can be implemented in an economical controller.

2.1. Steps followed in the proposed SSPO – SPPT algorithm:

The flow chart for the proposed technique is represented in Fig. 4. and the corresponding steps are explained briefly as follows:

Step 1: Initially, the algorithm measures the mode selection signal from the external controller. If it is global mode, then the algorithm initiates salp swarm perturb and observe (SSPO) [21] algorithm to track the maximum PV power irrespective of any irradiation condition. The SSPO algorithm is a hybrid algorithm used for tracking maximum power under uniform and partially shaded conditions. In the place of SSPO algorithm, any algorithms with good tracking capability can be used and tested.

If local mode is selected, the algorithm initiates the SPPT algorithm and tracks the power reference (P_{ref}) sent from the external controller.

Step 2: In this step, the instantaneous values of PV voltage (V_{pv}) and PV current (I_{pv}) are measured from the PV panel and the corresponding PV power (P_{pv}) is calculated. Additionally, change in power (dP_{pv}) and change in voltage (dV_{pv}) at that instant are calculated.

Step 3: In this step, the algorithm compares the P_{ref} and P_{pv}. If the P_{ref} is greater than the available P_{pv}, then the algorithm cannot track the required power and hence it operates the converter in a predefined minimum duty cycle (d_{min}).

The selection of predefined d_{min} can be explained with the help of Fig. 3. The proposed algorithm is designed to operate at all irradiation conditions. Hence, the PV array used is simulated for various irradiations (low to high) and the corresponding P-V and current voltage (I-V) curves are presented in Fig. 3a and Fig. 3b, respectively. The SPPT algorithm always work on the right side of the MPP and hence the duty cycle with the lowest irradiation (200 W/m^2) is selected and it is designated as d_{min}. At any instant, if the algorithm cannot provide the required P_{ref} then it operates the converter at d_{min} and the corresponding power is delivered at the output.

If P_{ref} is less than P_{pv}, then the algorithm moves to step 4 to track the P_{ref}.

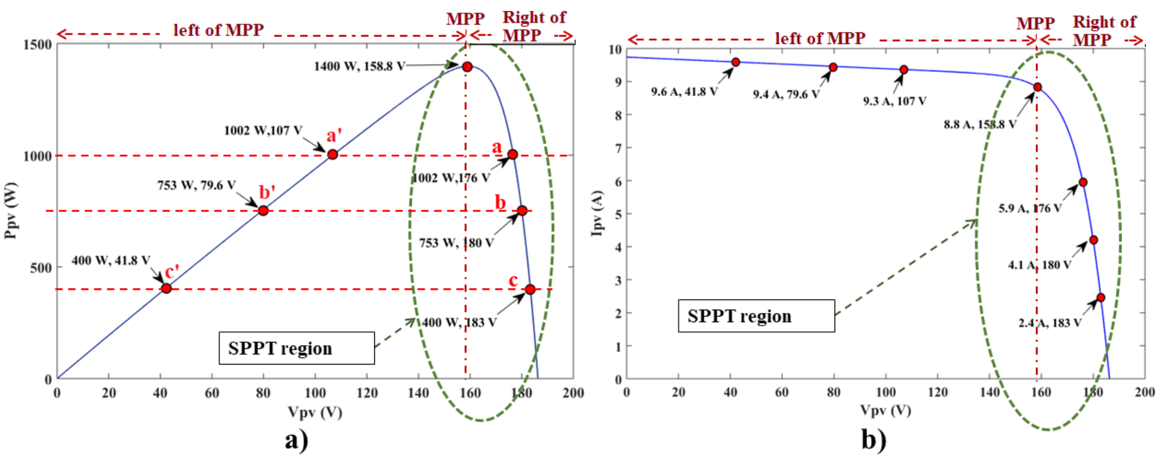


Fig. 2. a). Different voltage regions in a P-V curve. b). Different current regions in a I-V curve.

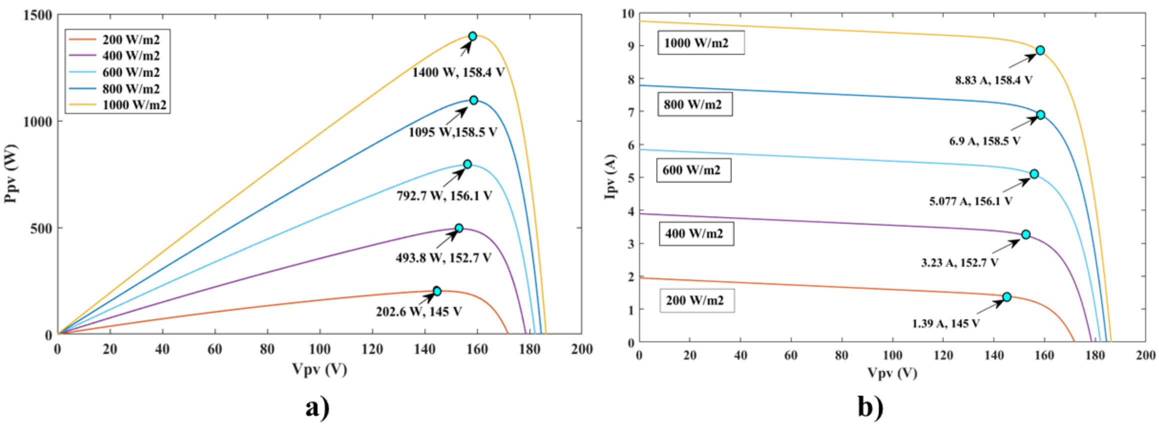


Fig. 3. PV module under different irradiation. a). P-V curve, b). I-V curve.

Step 4: The algorithm compares the P_{ref} with the current operating power (P_{pv}) of the converter using Eq. (1) [22]. The threshold value '0.2' in Eq. (1) is selected using multiple trial and error simulations. If the condition in Eq. (1) is satisfied, then the algorithm operates the converter at the current working duty cycle and if the condition is not satisfied, it moves to step 5 to track the P_{ref}.

$$\frac{|P_{pv} - P_{ref}|}{|P_{pv}|} < 0.2 \qquad (1)$$

Step 5*:* In this step, the algorithm measures the changes in dP_{pv} and dV_{pv} and correspondingly increase or decrease the duty cycle. The entire process (step 1 to step 5) continues and the duty cycle is updated for every sample time. Hence, after generating the new duty cycle at the end of step 5, the process again starts from step 1 in the next sample time. The algorithm stops updating the duty cycle when the P_{ref} is equal to P_{pv} and it is presented in step 4 of the flow chart. The algorithms continuously monitor the power under SPPT mode and it responds quickly when there is a change in P_{ref}. The main aim of the SPPT algorithm is to reduce the output power and to maintain high voltage and low current. Hence, the SPPT works in one direction (from high P_{ref} to low P_{ref}). If high power is required, then, automatically, the external controller selects the global mode and SSPO is used to search the global power.

3. Simulation Results and Discussion:

The performance of the proposed SSPO – SPPT algorithm is verified using the test system presented in Fig. 5. The algorithm controls power in the PV side and so, the inverter and load side control are not included in the circuit. The control algorithm takes 4 inputs V_{pv}, I_{pv}, mode selection and P_{ref}. The V_{pv} and I_{pv} value are required to calculate the power available in the PV system. So, the instantaneous values are sampled from the PV system periodically. The external controller or master controller monitors the overall system requirements such as power demand at the load side and power availability at the individual sources (in the case of hybrid power systems, multiple sources like PV and wind) connected to the system. The external controller calculates and sends the mode selection signal and the P_{ref} command

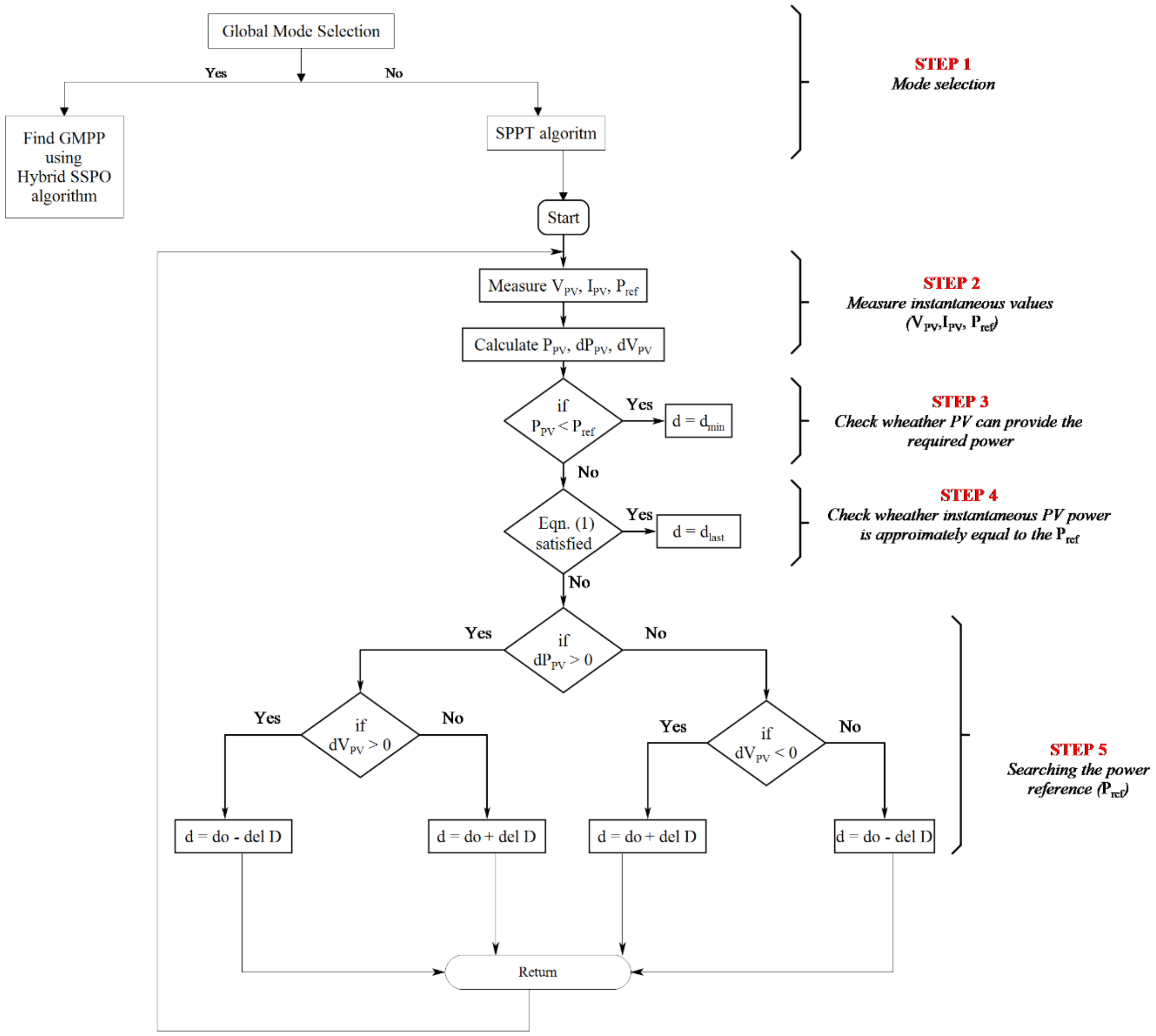


Fig. 4. Flowchart of combined SSPO – SPPT algorithm

based on the load side power variations. During partially shaded conditions, the maximum number of power peaks in the P-V characteristics is proportional to the number of PV panels connected in series. Hence, to evaluate the proposed algorithm under complex shading conditions, 4 PV panels are connected in series (4S configuration) in this work. The maximum peak power of a single PV module is 350 W and hence the total maximum power for 4S configuration used in simulation is 1.4 kW. The parameters of a single PV module are presented in Table 1. The values of the components used for designing the boost converter is shown in Table 2. In MATLAB simulation, 3 different analyses have been conducted and the results are discussed elaborately in the forthcoming sections.

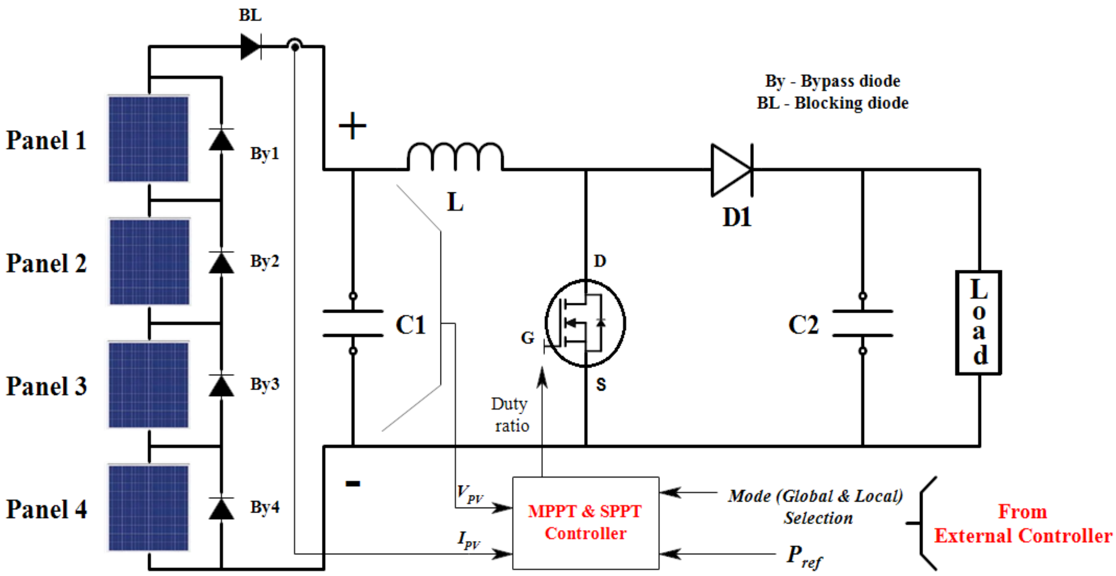


Fig. 5. Block diagram of test system used for simulation.

Table 1. PV module parameters

Parameter	Value
Short circuit current	9.74 A
Open circuit voltage	46.7 V
Current at MPP	8.83 A
Voltage at MPP	39.7 V
Power at MPP	350 W

Table 2. Boost converter parameters used in simulation

Parameters	Value
Input Capacitor (C1)	1 µF
Output Capacitor (C2)	100 µF
Inductor (L)	1 mH
Resistor (R)	250 Ω
Switching Frequency (fs)	20 kHz

3.1 Analysis I: Uniform irradiation

In analysis I, the performance of the SSPO – SPPT algorithm under uniform irradiation condition is tested. The irradiation is maintained constant at 1000 W/m^2 for all the 4 panels for a time period of 0 to 5s, and the corresponding P-V curve is presented in Fig. 6a. The global mode and the local mode operation are selected manually during the simulation and the mode selection signals are shown in Fig. 6b. During global mode SSPO algorithm is used to track the global power whereas, in local mode the SPPT algorithm is used to track the reference power command. The sequence of events from 0s to 5s is explained below.

1. Global mode (0 to 0.6s): Global mode is selected and the SSPO algorithm starts searching and converges at the global power (1398 W) available in the peak as shown in Fig. 7.

2. Local mode (0.6 to 3.6s): Local mode is selected and the SPPT algorithm starts searching the reference power. During the local mode, three different reference power commands at different time durations are given as follows: 800 W (0.6 to 1.1s), 600 W (1.1 to 2s) and 400 W (2 to 3.6s). In all the P_{ref} commands, the SPPT algorithm has tracked the corresponding PV power 790 W, 592 W and 394 W and the values are almost nearer to the reference commands. The tracked results (power (P_{pv}), voltage (V_{pv}), current (I_{pv})) are represented in Fig. 7. The SPPT algorithm works between the V_{mpp} and V_{oc} region and hence the variation in voltage is less. It is visible from Fig. 7 that under SPPT operation the voltage (V_{pv}) is almost maintained constant whereas the current (I_{pv}) is reduced towards the power reference.

3. Global mode (3.6 to 5 s): Again, the global mode is selected and the SSPO is reinitialized and finds the global power 1398 W.

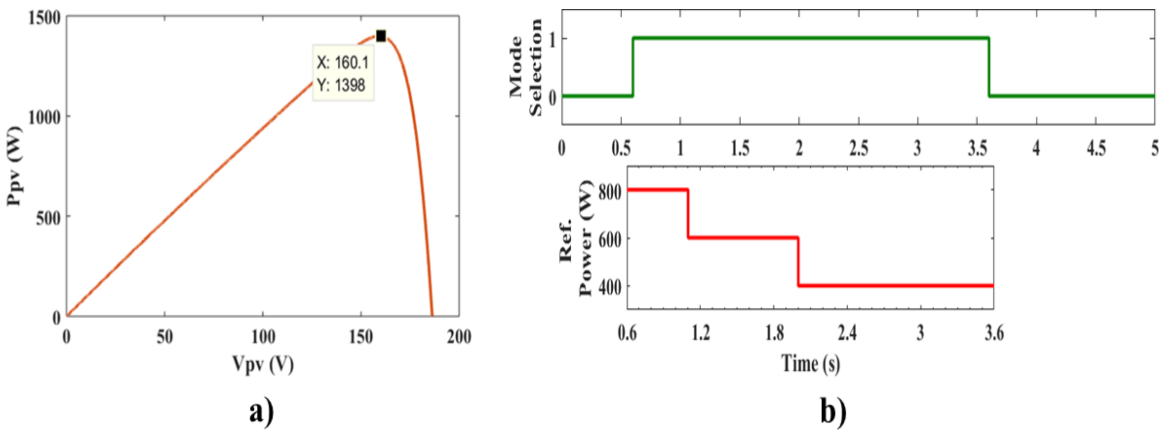


Fig. 6. a). P-V Characteristics. b). Mode selection signals

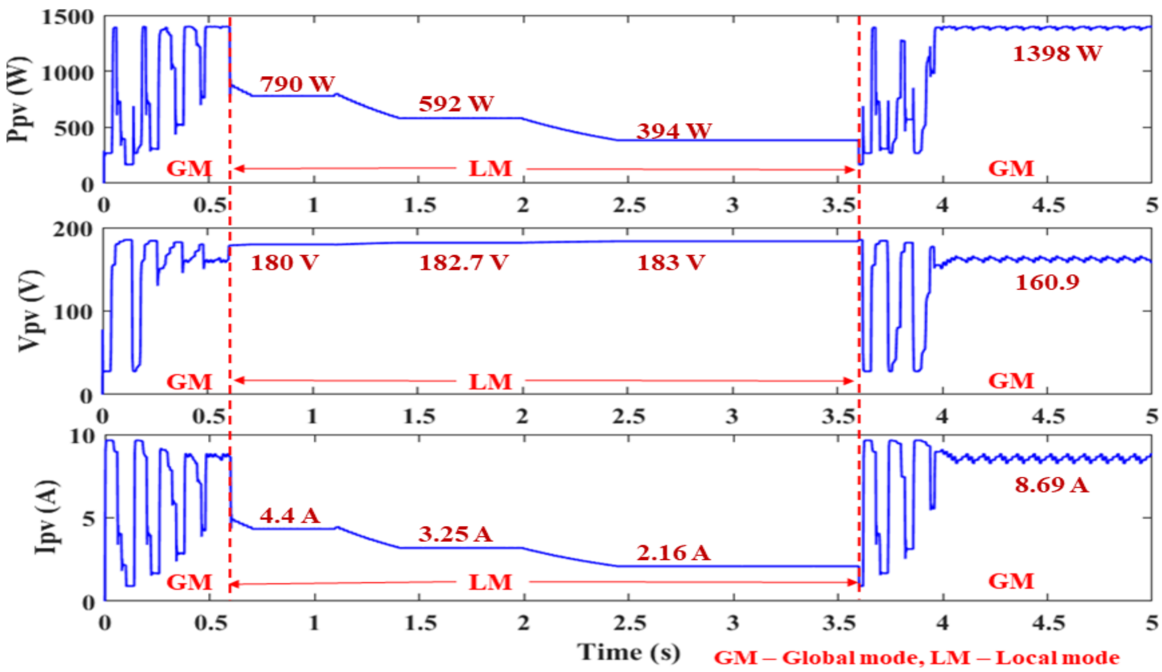


Fig. 7. Simulated waveforms for analysis I.

3.2 Analysis II: High to low irradiation

In analysis II, the performance of SSPO – SPPT algorithm under different irradiation levels is tested using two irradiation levels (pattern 1 and pattern 3). The irradiation value for pattern 1 is 1000 W/m^2 and for pattern 3 is 500 W/m^2 and the corresponding P-V characteristics is presented in Fig. 8a. In the total simulation time of 5s, pattern 1 is applied from 0 to 1.5s and pattern 3 is applied from 1.5s to 5s. The global mode and the local mode operation are selected manually during the simulation and the mode selection signals are shown in Fig. 8b. The sequence of events from 0s to 5s is explained below.

1. Global mode (0 to 0.6s): The SSPO algorithm is utilized to find the global power. The algorithm has tracked the maximum power 1398 W at 0.49s, as shown in Fig. 9.

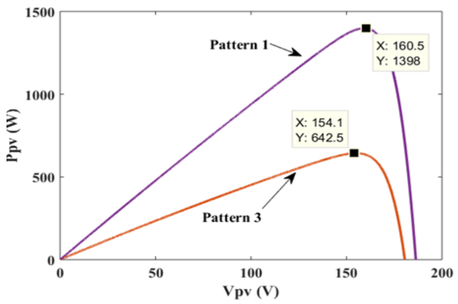
2. Local mode (0.6 to 1.1s): The SPPT algorithm is used for searching the reference power command. During this period (0.6 to 1.1s), the reference power command is 800 W and the algorithm has tracked 798 W (P_{pv}) as shown in Fig. 9.

3. Local mode (1.1 to 2s): The reference power for this duration is 600 W. Initially, the SPPT algorithm has tracked the reference power (600 W) in the P-V curve (pattern 1). At 1.5s, the irradiation is changed and pattern 3 is introduced. The SPPT algorithm detects the irradiation change and again tracks the reference power (600 W) in the new P-V curve (pattern 2). The effect of irradiation change is highlighted in the waveforms (P_{pv}, V_{pv} and I_{pv}) and it is shown in Fig. 9.

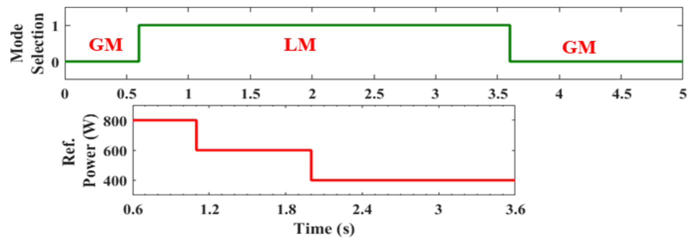
In pattern 3, the irradiation is less (500 W/m^2) and hence the position of power and voltage changes as shown in Fig. 8a. As a result, for the same reference power 600 W, the tracked voltage (V_{pv}) is reduced to 165 V and the current (I_{pv}) is increased to 3.7 A and it is shown in Fig.9. The results show the SPPT algorithm is effective in searching the P_{ref} under different irradiation levels.

4. Local mode (2 to 3.6s): The P_{ref} for this duration is 400 W. The SPPT algorithm has tracked the power (394 W) at the rightmost side of the pattern 2 P-V curves.

5. Global mode (3.6 to 5s): During this time period, Pattern 3 is available in the system with global power (642.5 W). The SSPO algorithm is initialized at 3.6s and has tracked the exact global power 642 W and it is shown in Fig. 9.



a)



b)

Fig. 8. a) P-V characteristics, b) Mode selection signals

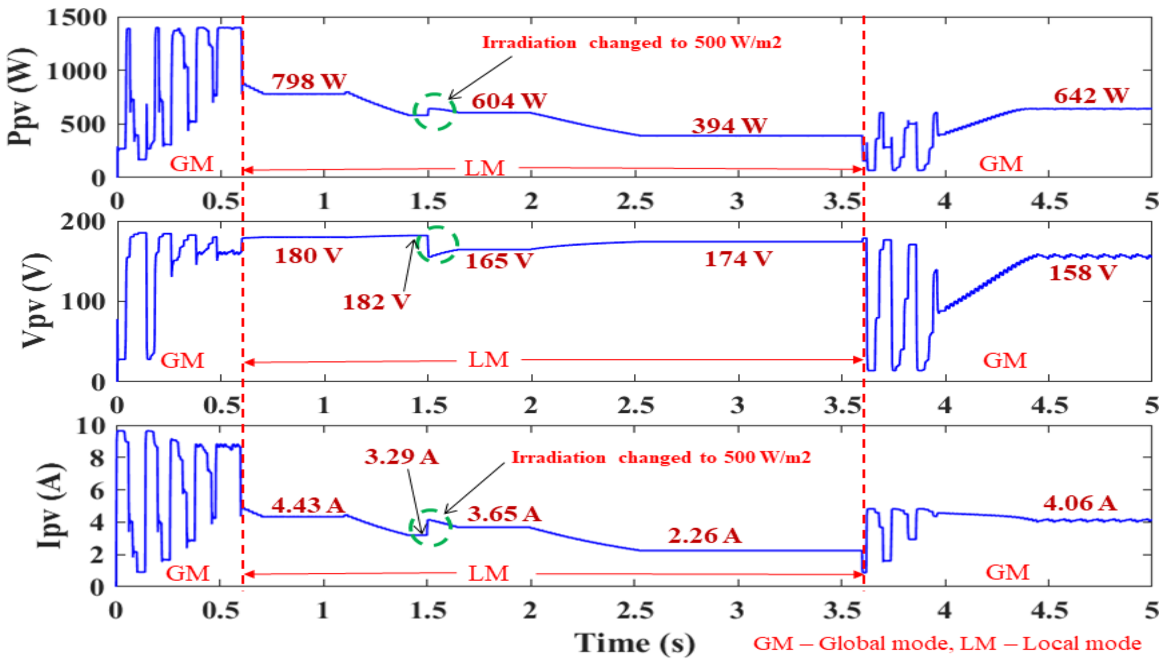


Fig. 9. Simulation results for analysis II

3.3. Analysis III: Shaded to uniform condition

In analysis III, the efficacy of the SSPO – SPPT algorithm under PSC condition is tested. The total simulation time is 5s. Initially, the uniform irradiation condition (pattern 1) is applied from 0 to 1.5s and then a partially shaded curve (pattern 4) is applied from 1.5s to 5s. When pattern 4 is introduced, the PV panels are treated with 4 different irradiation levels (1000 W/m^2, 800 W/m^2, 600 W/m^2, 400 W/m^2) and the corresponding P-V curve is shown in Fig. 10. The global and local modes are selected manually in the simulation. The sequence of events from 0s to 5s is explained briefly with the help of Fig. 10 and Fig. 11 as follows.

1. **Global mode (0 to 0.6s):** During this time period, the partially shaded P-V curve (pattern 4) is introduced. The SSPO is very efficient in tracking the global peak and hence it has tracked the exact global power (649.5 W) and it is highlighted in Fig. 10 and Fig. 11 with alphabet (a).

2. **Local mode (0.6 to 1.2s):** During this period, the P_{ref} is 800 W. In the local mode, the SPPT algorithm always searches the P_{ref} on the right side of the P-V curve. In pattern 4 P-V curve, the maximum power available in the peak is 568 W and it is less than the required P_{ref} (800 W). Hence, the SPPT algorithm executes step 2 of the flow chart (Fig. 4). Now, the boost converter is operated in the predefined duty cycle (0.3). The power available for the default duty cycle is 550 W and the operating point shifts to position (b), as shown in Fig. 11.

3. **Local mode (1.2 to 2s):** In this duration, the P_{ref} is 600 W and again it is greater than the available power. Hence, the algorithm continues to operate in the default duty cycle (0.3).

The irradiation pattern is changed to pattern 1 at 1.5s. At this point, the SPPT algorithm observes the power changes and settle down at the nearest reference value (592 W) in pattern 1 P-V curve. In the P-V curve (Fig. 10), the operating point shifts from position (b) to (c). The changes are highlighted in Fig. 11 as well.

4. **Local mode (2 to 3.6s):** The P_{ref} during this condition is 400 W. Since the P_{ref} is less, the SPPT algorithm has tracked the nearest power (394 W) easily. In the P-V curve the operating point now shifts from (c) to (d). Since the operating points (c) and (d) in the P-V (Fig. 10) are nearer to each other, the variation in V_{pv} (X axis) is significantly less. Whereas the current values are reduced towards the P_{ref}.

5. **Global mode (3.6 to 5s):** The global mode is initiated and the SSPO algorithm tracks the exact global peak (1396 W). In the P-V curve (Fig. 10), the operating point now shifts from (d) to (e).

Analysis III shows that the proposed SSPO – SPPT algorithm is efficient in tracking partial shaded conditions.

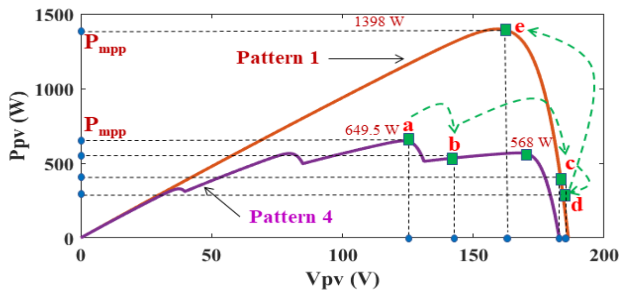


Fig. 10. Analysis III working representation in P-V characteristics

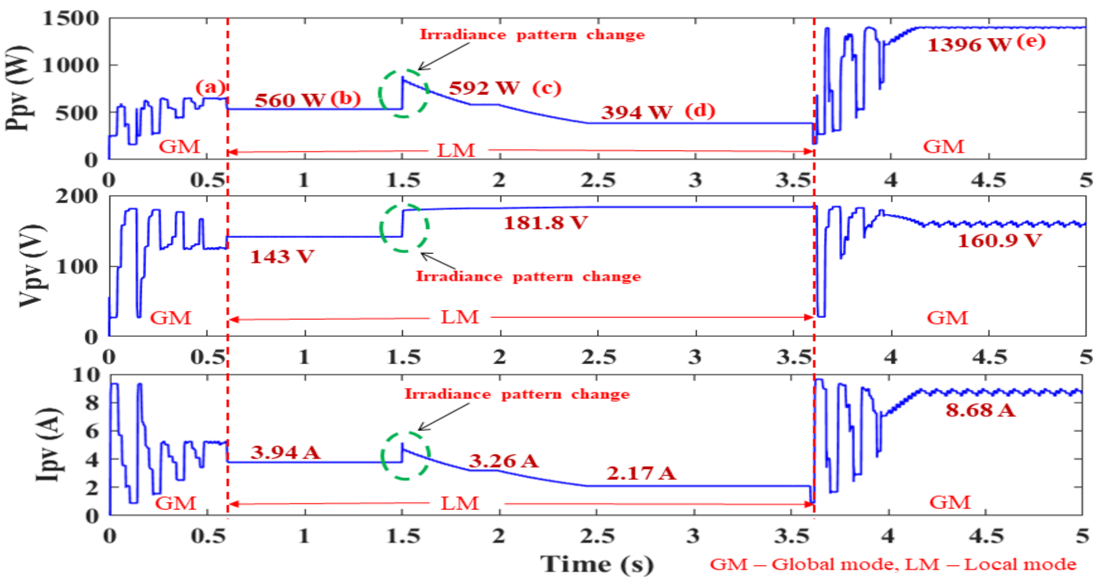


Fig. 11. Simulated results for analysis III.

4. Comparative Study

The tracking results of analysis I to analysis III are tabulated in Table 3 to Table 5. It can be observed that the tracking time for all the 3 analyses is less than 1s. The tracking error under global mode is significantly lower than in the local mode. In the local mode, the convergence criterion is fixed by a threshold value. Hence, when the algorithm reaches the nearest power reference value and satisfies the Eq. (1), it stops incrementing the duty cycle. Therefore, the tracking error exists in local mode SPPT operation. The tracking error can be further reduced by fine-tuning the Eq. (1) or using new methods.

Additionally, the performance of the proposed SSPO – SPPT algorithm is qualitatively compared with the other similar algorithms in the literature and it is presented in Table 6. In the proposed work, the steady state oscillation is significantly less when compared to other works. This is because the duty cycle variation is controlled once the approximate P_{ref} is tracked. The SPPT algorithm always operates on the right side of the PV curve and hence the voltage fluctuations are significantly reduced. The simulation results and the analysis show the suitability of the proposed algorithm in PV reduced power control operation.

Table 3. Tracking results of analysis I

Analysis	Mode	Algorithm	Time Duration (s)	Reference Power (P_{ref}) (W)	Tracked power (P_{pv}) (W)	Tracking Time (s)	Tracking error (%)
I	Global mode	SSPO	0 to 0.6	1398	1398	0.5	0
	Local mode	SPPT	0.6 to 1.1	800	790	0.1	1.25
			1.1 to 2	600	592	0.3	1.3
			2 to 3.6	400	394	0.4	1.5
	Global mode	SSPO	3.6 to 5	1398	1398	0.55	0

Table 4. Tracking results of analysis II

Analysis	Mode	Algorithm	Time Duration (s)	Reference Power (P_{ref}) (W)	Tracked power (P_{pv}) (W)	Tracking Time (s)	Tracking error (%)
II	Global mode	SSPO	0 to 0.6	1398	1398	0.5	0
	Local mode	SPPT	0.6 to 1.1	800	798	0.1	0.25
			1.1 to 2	600	604	0.38	0.66
			2 to 3.6	400	394	0.56	1.5
	Global mode	SSPO	3.6 to 5	642.5	642	0.8	0.07

Table 5. Tracking results of analysis III

Analysis	Mode	Algorithm	Time Duration (s)	Reference Power (P_{ref}) (W)	Tracked power (P_{pv}) (W)	Tracking Time (s)	Tracking error (%)
III	Global mode	SSPO	0 to 0.6	649.5	648	0.5	0.2
	Local mode	SPPT	0.6 to 1.1	800	S3*	S3*	S3*
			1.1 to 2	600	592	0.84	1.3
			2 to 3.6	400	394	0.4	1.5
	Global mode	SSPO	3.6 to 5	1398	1396	0.6	0.13

S3* - P_{pv} is less than P_{ref} and the algorithm cannot track the required power. Hence it operates the converter at default duty cycle as explained in step 3 of Fig. 4.

Table 6. Quantitative comparison of proposed algorithm

Algorithms	Reduced Power method	Direct Power Control method	Intermediate Power Tracking method	Binary Search method	Proposed method
Operating Region in the P-V curve	right	right	Both	Both	right
Dynamic response	Moderate	fast	fast	fast	fast
Steady state oscillations	less	high	less	less	less
Tracking error	Less	high	less	less	less
Complexity	less	less	moderate	complex	less
Tracking under partial shaded condition	No	No	yes	No	yes

5. Conclusion

A new SSPO – SPPT algorithm is proposed for tracking global power and reduced power in PV systems. The performance of the algorithm is verified using three different analyses with complex irradiation patterns. The results show that the tracking efficiency is greater than 98%, and the tracking time is less than 1s under both global and local modes. During local mode, the SPPT algorithm effectively tracks the reference power with less steady state error. The results show that the proposed control algorithm can effectively be used in PV system controllers to track reduced power during partial shading and different irradiation conditions.

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