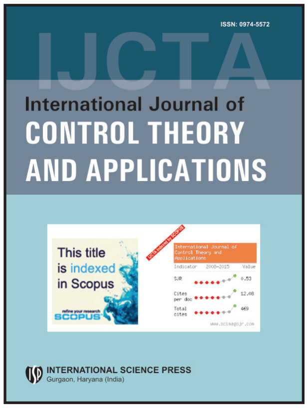

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A Dual-Stage PSO Based MPPT Algorithm for PV System under Partial Shaded Condition

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Abstract: Due to low efficiency and atmospheric dependency, photovoltaic (PV) systems are to be operated at maximum power point (MPP) to attain utmost benefit. MPPT controllers are generally used to extract maximum available power from PV system. Under partial shaded condition, PV characteristics exhibit multiple maxima in which only one is global MPP. Conventional MPPT controllers find difficulty to track global MPP under such conditions and they trap at local MPP, which decreases the efficiency of PV system. In literature several Swarm Intelligence (SI) based MPPT algorithms are proposed by authors, the main drawback associated with SI algorithms is inconsistency and larger tracking time due to random initialization and large population size. In order to overcome this problem an improved MPPT algorithm based on PSO i.e., Dual-Stage Particle Swarm Optimization (DPSO) to track MPP under both uniform irradiance and partial shaded condition is proposed in this paper. Application of DPSO MPPT algorithm and results obtained with it are analyzed in detail in this paper. The analytical modeling of PV system and proposed MPPT algorithm are simulated in MATLAB programming environment. The performance of proposed DPSO MPPT algorithm is compared with conventional PSO and Perturb and Observe MPPT algorithms and results proved its superiority.

Keywords: Maximum power point tracking; Photovoltaic system; Partial shaded condition; Two diode model; Dual-stage PSO (DPSO) algorithm.

1. INTRODUCTION

Solar energy is a growing non-conventional energy in the area of power generation due to several advantages. A single photovoltaic cell is insufficient for any application, hence number of cells are connected in series and parallel combination in a module and PV modules in series and parallel combination form PV array which is used to obtain desired power level for any application. Due to low efficiency and atmospheric dependency, PV systems are subjected to operate at maximum power point (MPP) to attain utmost benefit. As the characteristics of PV system are non-linear in nature, MPPT controller in conjunction with converter is necessary to operate PV system at MPP. From literature several conventional MPPT controllers like Perturb and observe (P&O), Hill climbing (HC) and Incremental conductance (INC) etc., can effectively track MPP under uniform irradiance condition in which PV characteristics exhibit only one MPP [1, 2].

Partial shading condition (due to passing clouds, buildings, bird waste etc.,) adversely deteriorates the efficiency of PV system, in which shaded modules acts as sink rather than a source. This phenomenon exhibits multiple maxima in PV characteristics due to bypass diode operation across shaded PV modules in order to prevent from hot spots [3]. In such a condition conventional MPPT controllers fail to track global MPP as they are designed for single MPP and may converge at local MPP, which leads to wastage of viable power and therefore efficiency of PV system is reduced.

In literature, several MPPT controllers are proposed to track global MPP under partial shaded condition [4, 5], out of which due to reduced complexity and simple hardware implementation Swarm Intelligence (SI) based MPPT algorithms are gaining more interest. The Authors in [6] are the first to propose biological swarm chasing algorithm for MPPT of PV system. There are several such algorithms employed for this problem, but most predominantly used is the Particle Swarm Optimization (PSO) based MPPT controllers due to its simplicity and increased tracking speed. Hence few researchers employed PSO and its improved versions to improve tracking efficiency considering voltage or duty cycle as decision variable [7-13]. The main drawback of PSO and all SI MPPT algorithms is their consistency and speed of tracking global MPP is always uncertain due to random initialization of population in the solution space and larger population size.

In order to address above problem in tracking global MPP, a novel improved PSO algorithm i.e., Dual-stage Particle Swarm Optimization (DPSO) is proposed in this paper which further increases the consistency of PSO MPPT algorithm. In DPSO, population is initialized uniformly over the search space to start the search process with good initial estimate in first stage. In second stage i.e., Dormant stage best particles in the entire population are obtained by comparing their fitness values, these contribute to the search process of global MPP with less number of iterations and in less time. For proper diversification and intensification, parameters of DPSO are taken suitably and tuned during iterations, helps in faster tracking of global MPP. In the proposed algorithm, voltage of PV system is taken as a decision variable to obtain maximum power. The proposed DPSO algorithm offers several advantages: (1) Due to uniform distribution of population, consistent tracking of global MPP is always guaranteed, (2) Dormant stage makes less number of particles participate in search process, leads to less number of steps and less tracking time, (3) Simple in structure.

The rest of the paper is organized as follows: PV system modeling under uniform irradiance and PSC are discussed in section 2, Section 3 briefly introduces the conventional PSO algorithm and proposed DPSO algorithm, Section 4 describes application of the proposed DPSO algorithm for MPPT problem followed by results and comparison with conventional PSO and P&O MPPT algorithms in section 5 and followed by conclusion in section 6.

2. CHARACTERISTICS OF PV SYSTEM UNDER PSC

2.1. PV Module

Single diode model (SDM) is most predominantly used in modeling of PV system due to its simplicity and computational efficiency. Besides its advantages, SDM has several disadvantages like reduced accuracy at low irradiance condition; it neglects carrier recombination loss and reduced performance with temperature variations [14]. In this paper a novel simplified two diode model (TDM) of PV module developed by Chitti babu et. al. [15] by neglecting series and shunt resistance is used to model PV system.

The equivalent circuit of proposed TDM is depicted in Figure 1.

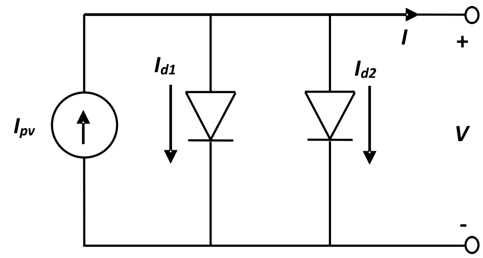

Figure 1: Equivalent circuit of TDM PV cell

The PV module output current is

$$I = I_{PV} - I_{01}\left[e^{\frac{qV}{N_s KTA_1}} - 1\right] - I_{02}\left[e^{\frac{qV}{N_s KTA_2}} - 1\right] \tag{1}$$

where, V is PV output voltage in volts, I is PV output current in amperes, I_{PV} is Photo current of PV module, I_{01} and I_{02} are Reverse saturation currents of diodes 1 and 2, T is PV module temperature in Kelvin, K is Boltzmann constant (1.38×10^{-23} N-m/K), A_1 and A_2 are Ideality factor of diodes 1 and 2, q is Electron charge (1.6×10^{-19} C) and N_s is Number of series connected cells in a module.

The photo current I_{PV} is given as

$$I_{PV} = (I_{PV\_STC} + k_i \Delta T)\frac{G}{G_{STC}} \tag{2}$$

where, k_i is Short-circuit current constant, I_{PV_STC} is Photo current of PV module at standard test condition (STC), ΔT is Temperature difference between T and T_{STC} (in Kelvin), G is Surface irradiation and G_{STC} is Surface irradiation at STC.

The reverse saturation currents of diodes are obtained using (3) and (4) [15].

$$I_{01} = \frac{I_{SC\_STC} + k_i \Delta T}{e^{(V_{OC\_STC} + k_v \Delta T)q/(N_s KTA_1)} - 1} \tag{3}$$

$$I_{02} = \left(\frac{T^{2/5}}{3.77}\right) I_{01} \tag{4}$$

where, I_{SC_STC} is Short circuit current of PV module at STC, V_{OC_STC} is Open circuit voltage of PV module at STC and k_v is Open-circuit voltage constant. The specifications of Kyocera KC200GT PV module are taken from [15].

2.2. Uniform Irradiance Condition

For any application a single solar cell is insufficient. To attain greater output voltage number of PV cells are connected in series to form PV module. In PV applications to attain required power rating, PV modules are connected in series and parallel to form PV array.

The characteristics of PV array subjected to uniform irradiance can be obtained by

$$I = N_{pp}\begin{bmatrix} I_{PV} - I_{01}\left[e^{\frac{qV}{N_{ss} KTA_1}} - 1\right] \\ -I_{02}\left[e^{\frac{qV}{N_{ss} KTA_2}} - 1\right] \end{bmatrix} \tag{5}$$

where, N_{pp} and N_{ss} are number of parallel and series connected modules in PV array.

2.3. Partial Shaded Condition

When PV array is subjected to PSC, the characteristics of PV array exhibits multiple maxima. Output characteristics of PV array under PSC assuming one bypass diode for each module are mathematically modeled by using the following sequential steps.

(i) Determine solar irradiance matrix by calculating G

(ii) Calculate I_{PV} of each module with respect to their irradiances using (2)

(iii) Sort I_{PV} matrix in descending order

(iv) Calculate output current of array, I using (6)

(v) Calculate output voltage of array, V using (7)

The output current and voltage of PV array are obtained by solving following equations [16].

$$I = \begin{cases} I_{PV}(G_n) - I_{01}\left[e^{\frac{qV_n}{N_s A_1 KT}} - 1\right] - I_{02}\left[e^{\frac{qV_n}{N_s A_2 KT}} - 1\right], & I > I_{PV_{n-1}} \\ I_{PV}(G_{n-1}) - I_{01}\left[e^{\frac{qV_{n-1}}{N_s A_1 KT}} - 1\right] - I_{02}\left[e^{\frac{qV_{n-1}}{N_s A_2 KT}} - 1\right], & I_{PV_{n-2}} < I < I_{PV_{n-1}} \\ I_{PV}(G_1) - I_{01}\left[e^{\frac{qV_1}{N_s A_1 KT}} - 1\right] - I_{02}\left[e^{\frac{qV_1}{N_s A_2 KT}} - 1]\right], & I < I_{PV_1} \end{cases} \tag{6}$$

$$V = \begin{cases} V_n & I > I_{PV_{n-1}} \\ V_n + V_{n-1}, & I_{PV_{n-2}} < I < I_{PV_{n-1}} \\ V_n + V_{n-1} + \ldots + V_1, & I < I_{PV_1} \end{cases} \tag{7}$$

3. PROPOSED DPSO ALGORITHM

3.1. Conventional PSO Algorithm

PSO is swarm intelligence based meta-heuristic algorithm inspired from bird flocking and fish schooling proposed by Kennedy et. al. [17]. In PSO a swarm of candidate solutions (particles) are initialized randomly in search space and these particles involve in search process to find optimal solution. PSO algorithm is mathematically represented by two equations that specify the position and velocity updates of a particle *i*.

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{8}$$

$$v_i^{k+1} = wv_i^k + c_1 r_1 \{P_{best,i} - x_i^k\} + c_2 r_2 \{G_{best} - x_i^k\} \tag{9}$$

where, k is the current iteration, w is inertia weight, c_1 and c_2 are learning parameters (cognition and social parameters), r_1, r_2 are random numbers, $P_{best,i}$ is personal best position of particle i, G_{best} is best position of the particle in entire population. The population of candidate solutions in conventional PSO algorithm is initialized using:

$$a + (b - a) \text{ rand } (N_p, D) \tag{10}$$

The movement of particles in the search process is depicted in Figure 2.

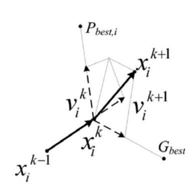

Figure 2: Movement of particles in search process

3.2. DPSO Algorithm

In conventional PSO Algorithm, population of candidate solutions is initialized randomly in the search space which leads to inconsistent tracking of optimal value and may convergence at local optima. In order to overcome this problem, uniform distribution one of the important symmetric probability distribution is used, in which all distributions have equal probability intervals [18]. In this approach entire population is distributed in equal intervals over the search space. The two stages in proposed DPSO algorithm are

(i) ***Initialization:*** Generate the population of candidate solutions uniformly between its minimum limit a and maximum limit b using the following expression.

$$\text{unifrnd}(a, b, N_p, D) \tag{11}$$

where, D is the number of decision variables and N_p is the size of population.

(ii) ***Dormant Stage:*** In this stage, evaluate objective function and fitness values of uniformly distributed population and obtain pair wise best population by comparing their successive fitness values. Population with undesirable fitness value will be in dormant state and doesn't contribute in the search process. The best candidate solutions thus obtained are treated as local best values, out of which one is global best value. Then start iterative process with these values as of conventional PSO by updating position and velocity using equations (8) and (9). In (8) and (9) r_1, r_2 random numbers are also initialized uniformly. This process of execution starts the search process with good initial estimate and converges in less number of steps and in less time.

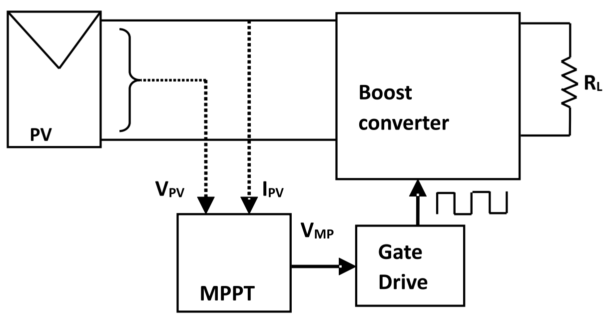

Figure 3: Block diagram of MPPT controller

4. APPLICATION OF DPSO FOR MPPT

For MPPT, a boost converter is connected between load and PV array as depicted in Figure 3. Voltage of PV array is considered as decision variable, output power of the PV array is considered as an objective function to be maximized and it is sensed and sampled for every 0.1s. Sequential steps for tracking global maxima using DPSO algorithm are as follows:

(i) *Initialization:* To epitomize the application of DPSO algorithm for GMPP tracking, first a solution vector of voltages is uniformly distributed between 10% $V_{oc,A}$ to 90% $V_{oc,A}$ using following expression.

$$\text{unifrnd}\,(0.1 \times V_{oc,A}, 0.9 \times V_{oc,A}, N_p, 1) \tag{12}$$

where, $V_{oc,A}$ is the open circuit voltage of array.

(ii) *Dormant stage:* The fitness function of DPSO algorithm is formulated as

$$P(V_i^k) > P(V_i^{k-1}) \tag{13}$$

where, P represents power, V is voltage, i is number of current particle. Using the dormant stage process, obtain local best (P_{best}) and global best (G_{best}) values of voltages.

(iii) *Updating:* Update the position and velocity of voltages by using equations (8) and (9). Initially high value of inertia weight w is considered for good exploration and decreased over course of iterations using (14). c_1 and c_2 are also updated over the course of iterations using (15) and (16) [19].

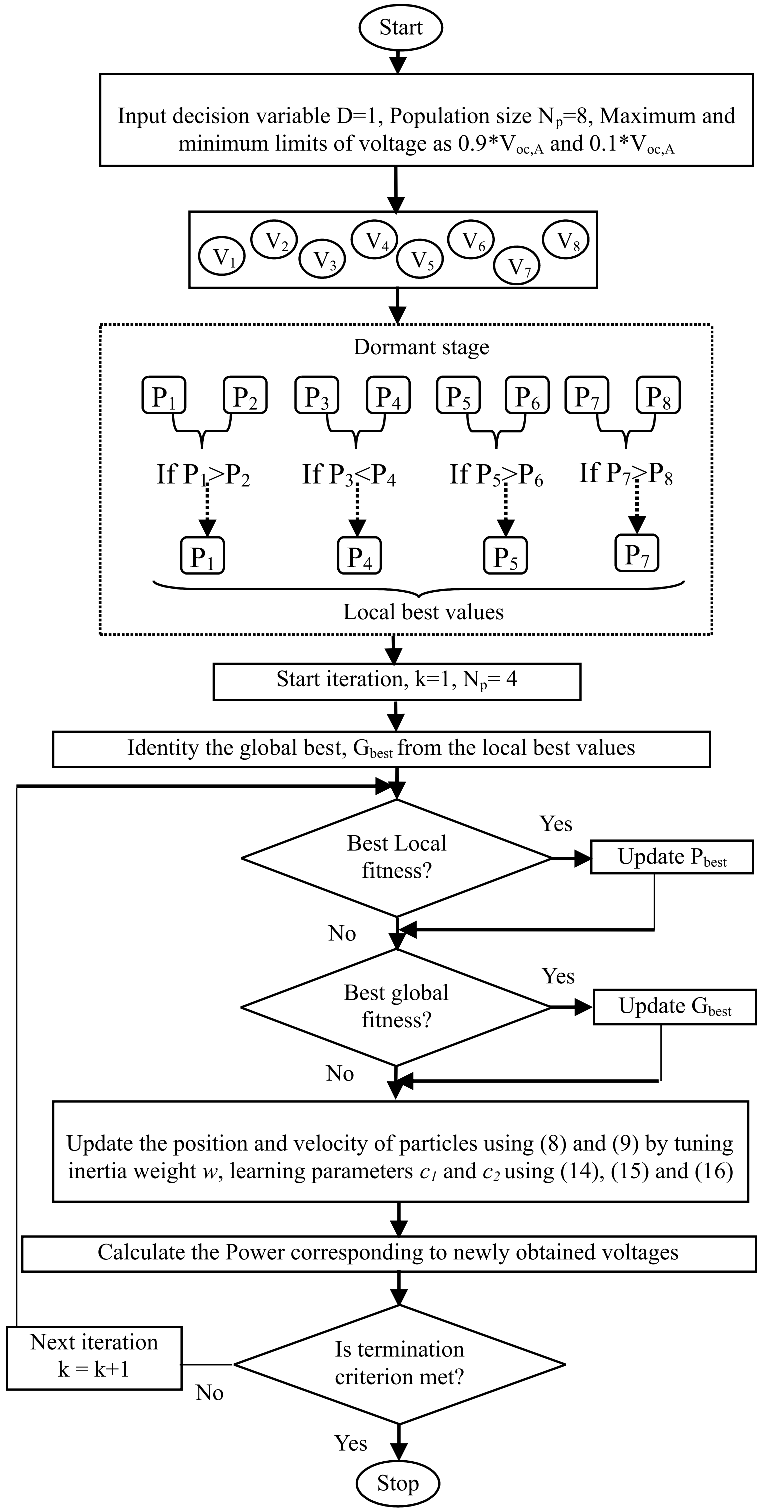

Figure 4: Flow chart of DPSO for MPP tracking

$$w = w_{max} - \frac{(w_{max} - w_{min}) \times k}{k_{max}} \tag{14}$$

$$c_1 = c_{1\,max} - \frac{(c_{1\,max} - c_{1\,min}) \times k}{k_{max}} \tag{15}$$

$$c_2 = c_{2\,min} + \frac{(c_{2\,max} - c_{2\,min}) \times k}{k_{max}} \tag{16}$$

(iv) *Termination criterion:* Algorithm terminates when number of iterations reaches its maximum value and then output corresponding voltage and its corresponding maximum power.

The parameters of proposed MPPT algorithm are given in Table 1. As number of population is critical parameter in deciding tracking ability, in order to avoid trapping at local maxima and for faster convergence it is chosen N_p same as number of PV modules in series array [10]. Decision variable as voltage, D = 1. The detailed methodology of the proposed DPSO algorithm in tracking MPP is depicted in Figure 4.

Table 1
Parameters of Proposed DPSO method

Parameter	*Proposed DPSO*
Initial Population (Voltage)	Uniformly distributed voltages between 10% to 90% of V_{oc}
N_p	8
$C_{1\,max}$	2
$C_{1\,min}$	1
$C_{2\,max}$	2
$C_{2\,min}$	1
W_{min}	0.1
W_{max}	1.0
Max number of iterations (k_{max})	100
Termination criterion	Max number of iterations

5. RESULTS AND COMPARISON

To examine the performance of proposed DPSO algorithm, numerical simulations were performed for MPPT of simple eight series (8S) PV array subjected to different shading patterns.

1. $G_1, \ldots, G_8 = 1000W/m^2$
2. $G_1, G_2 = 1000W/m^2$, $G_3, G_4 = 800W/m^2$, $G_5, G_6 = 600W/m^2$, $G_7, G_8 = 400\ W/m^2$
3. $G_1 = 1000W/m^2$, $G_2 = 800W/m^2$, $G_3 = 600W/m^2$, $G_4 = 500\ W/m^2$, $G_5 = 400W/m^2$, $G_6 = 300W/m^2$, $G_7 = 200W/m^2$, $G_8 = 100\ W/m^2$

(i) Pattern 1

The Power-Voltage (P-V) characteristics of PV array subjected to pattern 1 are depicted in Figure 5. From Figure 5, when modules in a series connected PV array are subjected to uniform shading, the characteristics of PV array exhibit one MPP. MPPT subjected to this pattern is obtained using proposed MPPT algorithm. From the tracking curves in Figure 6, the proposed method guarantees the MPP of 1604.9 W with less tracking time of 3.5 s.

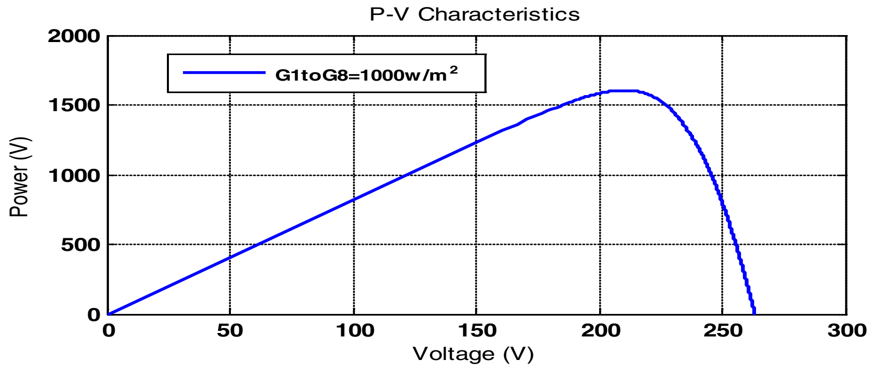

Figure 5: P-V characteristics of 8S PV configuration for pattern 1

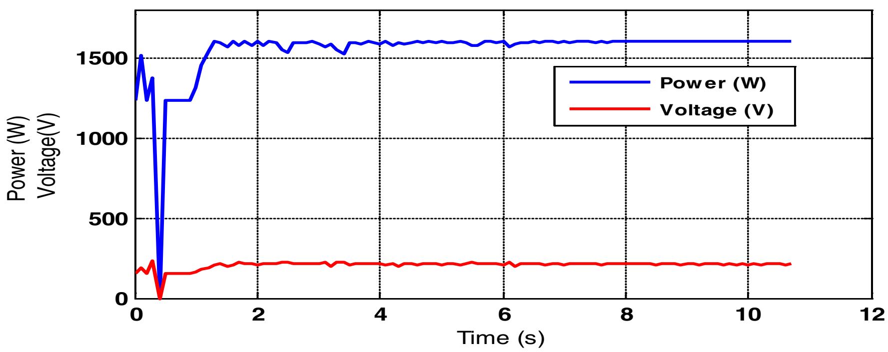

Figure 6: Tracking Curves of Power and Voltage for Pattern 1

It is clear that proposed MPPT algorithm can efficiently track MPP when PV array operating under this condition with good initial estimate and in less number of iterations and in less time.

For analysis, proposed MPPT algorithm is compared with conventional PSO and P&O MPPT algorithms under similar conditions. For fairness of comparison same number of population ($N_p = 8$) is considered for both conventional PSO and proposed DPSO algorithms and population is generated using (10) and (11) between 10% of $V_{oc,\,A}$ to 90% of $V_{oc,\,A}$. The performance comparative analysis of proposed DPSO MPPT, conventional PSO MPPT and P&O MPPT algorithms in terms of tracking speed, tracking steps and tracking efficiency subjected to this shading pattern are reported in Table 2.

Table 2
Performance Comparison of Proposed DPSO, Conventional PSO and P&O MPPT Methods

PV configuration	*Shading pattern*	*Tracking method*	*PV power (W)*	*PV voltage (V)*	*PV current (A)*	*Tracking time (s)*	*Tracking speed (steps)*	*Maximum power from P-V curve (W)*	*Tracking efficiency (%)*
8S		DPSO	1604.9	209.78	7.65	3.5	35		99.99
	1	PSO	1604.9	209.78	7.65	5.5	55	1605.15	99.99
		P&O	1604.5	209.5	7.65	1.9	19		99.99
		DPSO	800.28	166.34	4.81	3.2	32		99.99
	2	PSO	792.67	168.18	4.71	5.9	59	800.284	99.04
		P&O	401.5	52.5	7.65	1.1	11		50.13
		DPSO	459.24	141.80	3.23	3.3	33		99.99
	3	PSO	448.36	137.19	3.20	6.6	66	459.241	97.63
		P&O	200.5	26.5	7.55	0.8	8		43.68

(ii) Pattern 2

The P-V characteristics of PV array subjected to shading pattern 2 are depicted in Figure 7.

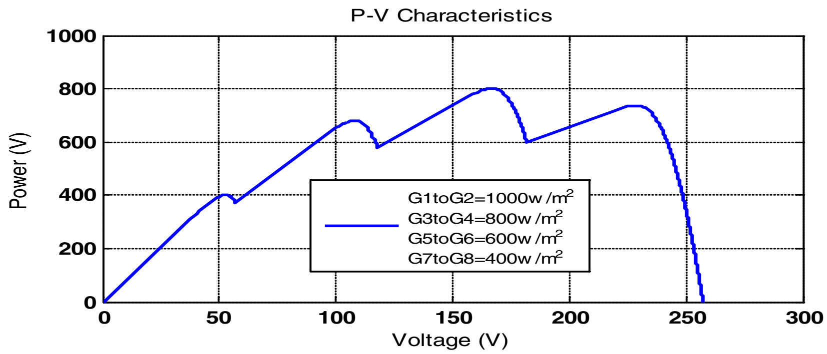

Figure 7: P-V characteristics of 8S PV configuration for pattern 2

From Figure 6 it is clear that, when a PV array is subjected to this shading pattern, output power from PV array decreases accordingly and PV array exhibits multiple maxima. Global MPP tracking subjected to this condition is obtained using proposed MPPT algorithm. From the tracking curves in Figure 8, the proposed method guarantees the global MPP of 800.28 W with less tracking time of 3.2 s.

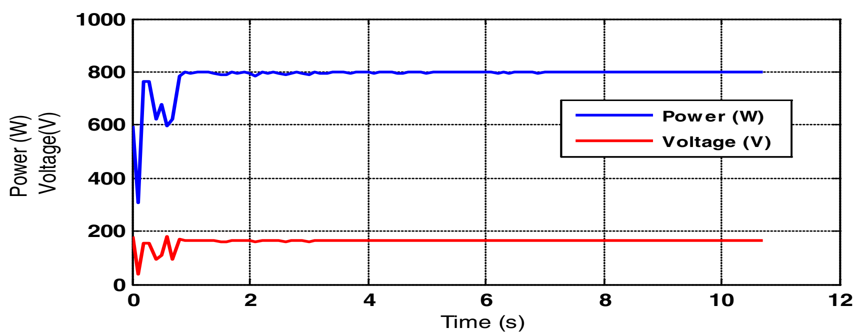

Figure 8: Tracking Curves of Power and Voltage for pattern 2

It is clear that proposed MPPT algorithm can efficiently track global MPP when PV array operating under this condition with good initial estimate and in less number of iterations. The comparative results subjected to this shading pattern are reported in Table 2.

(iii) Pattern 3

The P-V characteristic of PV array subjected to shading pattern 3 is depicted in Figure 9.

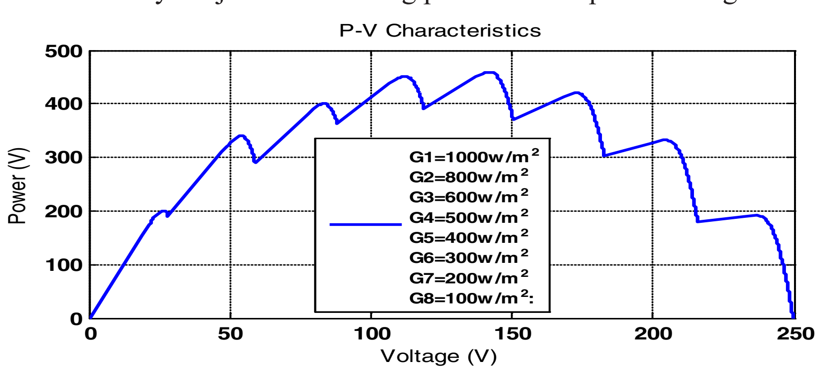

Figure 9: P-V characteristics of 8S PV configuration for pattern 3

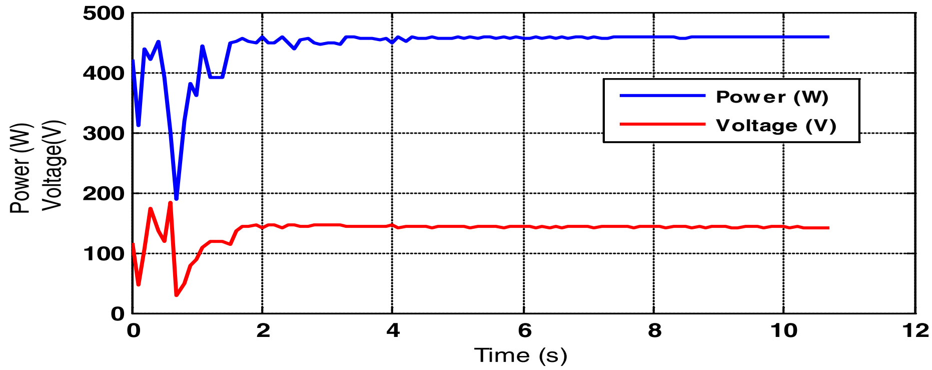

Figure 10: Tracking Curves of Power and Voltage for pattern 3

From Figure 9 it is clear that, when a PV array is subjected to this shading pattern, output power from PV array decreases accordingly and PV array exhibits multiple maxima. GMPP tracking subjected to this condition is obtained using proposed MPPT algorithm. From the tracking curves in Figure 10, the proposed method guarantees the global MPP 459.24 W with less tracking time of 3.3 s.

It is clear that proposed MPPT algorithm can efficiently track GMPP when PV array operating under this condition with good initial estimate and in less number of iterations. The comparative results subjected to this shading pattern are reported in Table 2.

From Tables 2, it is clear that proposed DPSO MPPT algorithm has superior tracking efficiency of 99.99% and superior tracking speed than both conventional PSO and P&O MPPT algorithms. Here tracking efficiency is defined as ratio of maximum power obtained from algorithm to maximum available power of the PV array configuration [10].

The graphical representation of maximum power extracted and time for tracking the MPP by all MPPT algorithms are depicted in Figure 11 and Figure 12. From Figure 11, it is clear that maximum power extracted by proposed algorithm is more accurate than conventional PSO and P&O MPPT algorithms. From Figure 12, it is also noticed that time for tracking the MPP by proposed algorithm is very less compared to conventional PSO and P&O MPPT algorithms.

As SI based algorithms are stochastic, simulations for both algorithms are carried out for 100 trail runs. The mean maximum power tracked by proposed MPPT algorithm varies with very low standard deviation for 100 trail runs but maximum power tracked by conventional PSO MPPT has very high standard deviation compared to proposed MPPT.

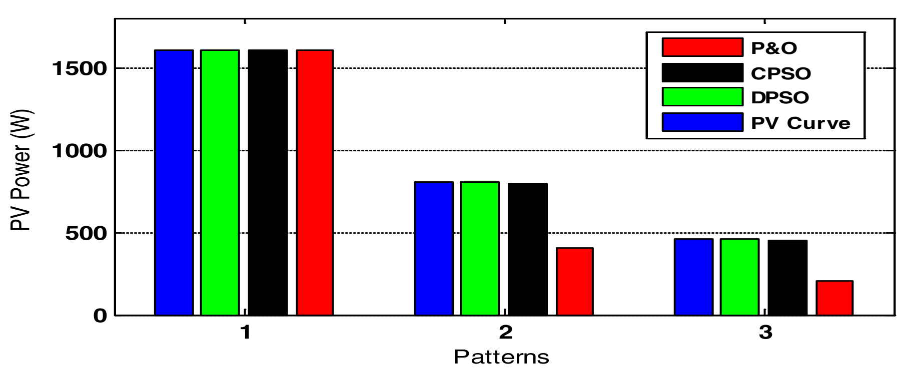

Figure 11: Maximum power obtained by DPSO, conventional PSO and P&O MPPT methods

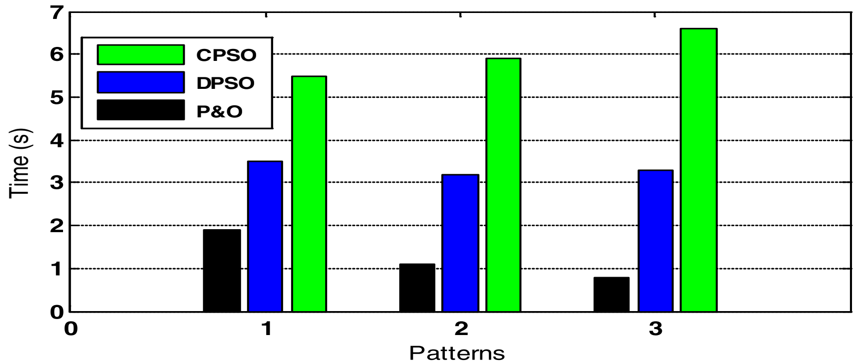

Figure 12: Tracking time for DPSO, conventional PSO and P&O MPPT methods

6. CONCLUSION

In this paper a novel DPSO MPPT algorithm is proposed to track MPP of PV array subjected to different shading patterns. Mathematical simulation is carried out in MATLAB programming environment for 8S PV configuration and MPP tracking clearly evince that proposed algorithm is superior to conventional PSO and P&O MPPT algorithms in terms of tracking efficiency, tracking time and tracking speed. The proposed algorithm has better initial estimate and reduced population participation in the search process due to uniform distribution and dormant stage initialization leads to reduced time of tracking the MPP and with superior efficiency over conventional PSO and P&O MPPT algorithms. The proposed algorithm has very low standard deviation for 100 trail runs performed. The tracking curves and graphical performance analysis clearly indicates the superiority of proposed algorithm over conventional PSO and P&O MPPT algorithms.

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