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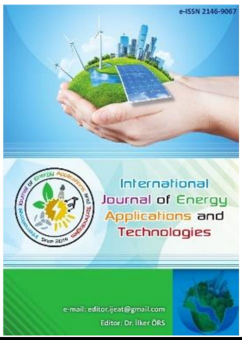

Original Research Article

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Enhanced particle swarm optimization and P&O for MPPT of photovoltaic systems under partial shading conditions

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ABSTRACT

Although Photovoltaic Technologies are largely deployed as a renewable energy source, several factors affect their performance. The major factors that affect PV performance are changes in irradiance and temperature. Maximum PowerPoint Tracking of PV output is essential in giving the maximum photovoltaic outputs at variable levels. Instantaneous variation in irradiance and temperature increases the complexity of tracking maximum power points. Partial shading conditions resulting from shade from trees, tall buildings, and Cloud formation amongst others greatly affect PV systems, especially in large Photovoltaic systems. Under the Partial shading condition, P-V curves become more complex as it is characterized by multiple peaks. The conventional PSO is associated with less accuracy in tracking the Global Maximum Power Point (Global MPP) and slow convergence time in obtaining the Global MPPT and oscillations. In this thesis, a modified Particle Swarm Optimization based Maximum Power Point Tracking technique is designed in MATLAB/Simulink to track the global Maximum Power Point of a Photovoltaic system under partial shading. The proposed modified PSO combines conventional PSO and P&O methods. The particle position in the PSO method is given as the duty cycle value d of the DC-DC converter. Conventional PSO equations are used to update the velocities and duty cycle. Thereafter, the maximum velocity and duty cycle are perturbed to reduce convergence time. The designed PV system was simulated in a MATLAB environment for 10 different irradiation levels and results were compared with results from related works. The average convergence time was 0.99 seconds and efficiency was up to 99.8% with the proposed model which performed better than conventional methods.

Keywords: PV system; MPPT; Partial shading condition; Global MPPT; PSO

1. Introduction

As the demand for energy increases and fossil fuels are depleted, the world is scrambling for alternative energy sources to meet the rising demand. Solar energy is the most subscribed and abundant permanent source of renewable energy [1]. Photovoltaic technologies are mainly deployed to harness energy from the sun and convert it into electrical energy through an electronic process [2]. Several factors determine the workability of a photovoltaic system, and one of these factors is the change in irradiance and temperature. The Maximum Power Point Tracking (MPPT) of a PV generation system is an important aspect when discussing PV systems [3, 4]. Tracking the maximum power point becomes complex as these characteristics change over time. Partial Shading Condition is one of the conditions that have a significant impact on the P-V characteristics of photovoltaic systems. Some parts of the PV systems may receive less irradiance from the sunlight due to the shadows of trees, tall buildings, poles, moving clouds, or neighboring modules. In series-connected arrays, the shaded panel could act as a load to the system. The PV curve is more complex in this condition as it is characterized by multiple peaks. The multiple peaks originated from the actuation of the bypass diodes to avoid shaded cells from damaging [5, 6]. The effectiveness of conventional MPPT algorithms is reduced with the appearance of multiple peaks. Traditional MPPT algorithms such as Perturb and Observe (P&O) [7], Incremental Conductance (IncCond) [8], open-circuit voltage, and short-circuit current lack the capacity to accurately track the global maximum. Additionally, these algorithms oscillate around the MPP and possess a long convergence time, thereby reducing the efficiency of the system under varying atmospheric conditions. Researchers have developed advanced MPPT techniques to track MPP under varying atmospheric conditions as discussed in the following paragraphs [9-22].

To overcome the problem of ineffectiveness under variable insolation, Vanxay et al. presented an improved PSO. The authors added a repulsion term to the standard equation of PSO to improve the response to varying insolation. Although the improvement shows better performance, low cost, and high overall efficiency, the addition of various extra coefficients to the conventional PSO equations increased the computation of the algorithm [9].

Yupeng Liu et al. proposed a variable size strategy. The work increased the movement step of particles at the initial iteration to increase the diversity of particles and gradually decreased it with iterations. Additionally, the authors developed an objective function expression dependent on PV current, solar irradiation, and temperature. As a result, the MPP can be tracked more quickly and accurately. However, the expression given to evaluate the fitness of the solution equivalent to the operating power point is not reflected. Therefore, the tracking of the real peak power is not certain [10].

Kashif Ishaque et al. also submitted an approach to address the decrease in particle velocities after locating the MPP. The attempt used direct duty cycle control in conjunction with PSO. The duty cycle was kept at a constant value at MPP, which eradicated steady-state oscillation and improved system efficiency. However, the approach did not address the long tracking time to locate MPP [16].

Kobayashi et al. proposed the two-stage MPPT control method to tackle the convergence time problem in other MPPT algorithms. The PV system's operating point is moved closer to MPP on the load line R_m in the first stage, and it converges at MPP in the second stage. The research adopted the concept of the proportionality between the open-circuit voltage V_oc and the short-circuit current I_sc to an equivalent R_m. The method achieved good results in tracking the maximum power point under rapidly changing insolation but contributes to the system's complexity (i.e., additional circuitry for measuring open-circuit voltage and short-circuit current) [11].

Kashif Ishaque proposed the use of PSO to track the Global Maximum Power Point under PSC. The performance is assessed using MATLAB/Simulink simulation and was implemented in grid-connected PV systems that use a boost DC-DC converter to track the global optimum. For MPPT, the P-I characteristics curve was used. The results show that the MPPT algorithm successfully tracked the GMPP under both uniform and variable insolation conditions.

Musa Abdulkadir devised a modified PSO algorithm that reduces the weighting factor, as well as cognitive and social characteristics, to speed up convergence. The approach was implemented in MATLAB/Simulink, and the results show that the iteration steps were reduced, and the speed of convergence was improved [12].

The proposed algorithm aims to improve the accuracy and convergence time of the traditional PSO algorithm for tracking the Global MPP under partially shaded conditions. This is based on the improvement of the controller algorithm responsible for computing the duty cycle value per sample time. The proposed algorithm combines the conventional PSO and a P&O algorithm to further perturb the values of the updated maximum velocities and positions for accuracy in tracking and to improve convergence time. Detailed modeling of the PV system is given and designed using MATLAB/Simulink software. The modeled system is placed under different irradiation patterns to validate the performance of the proposed algorithm. Comparisons with other literature were carried out.

Model of a PV Cell

The most common PV cell model is a single diode, and it is normally used to establish I-V curves. Fig 1 depicts an equivalent circuit for a single-diode model [10, 13].

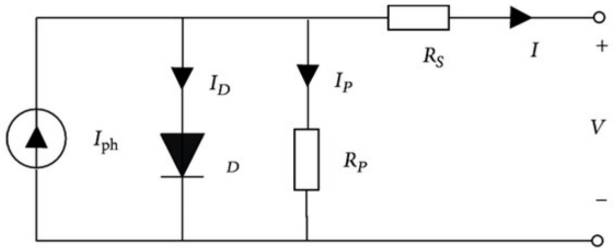

Fig. 1. Single diode circuit of a PV model

The output current I is expressed as:

$$\mathrm{I} = \mathrm{I_{Ph}} - \mathrm{I_d} - \mathrm{I_p} \tag{1}$$

Where,

$$\mathrm{I_{Ph}} = \mathrm{I_{SC}} + \mathrm{k_i} * (\mathrm{T} - 298).\frac{\mathrm{G}}{1000} \tag{2}$$

$$\mathrm{I_d} = \mathrm{I_o}[\exp\left(\frac{V+IR_s}{n_s.V_T}\right) - 1] \tag{3}$$

$$\mathrm{I_{sh}} = \frac{V+IR_s}{R_p} \tag{4}$$

I_{sc} is the short circuit current. I_{Ph} is the generated current from the PV system by the incident of sunlight. I_o is the reversed saturation current of the diode. n_s represents the diode ideality constant. V_T is the thermal voltage of the PV module having several series-connected cells, N_s.

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$$V_T = {}^{N_s.kT}/_{q} \quad (5)$$

The R_s is introduced to consider the voltage drop and internal losses due to the flow of current. When a diode is in the reverse direction, R_P considers the current that leaks to the earth.

$$I_o = kT^m(e^{-(V_{GO}+IR)}/_{nV_T}) \quad (6)$$

Where $I_o$is the reverse saturation current, $V_{GO}$is the bandgap energy, and k is a constant.
Equation (1) becomes:

$$I = \mathrm{I_{Ph}} - \mathrm{I_o}[\exp\left(\frac{V+IR_s}{n_s.N_s.k.T}\right)q - 1] - \frac{V+IR_s}{R_p} \quad (7)$$

Where q is the electron charge, k is Boltzmann constant $(1.38 \times 10^{-23} J/k)$ and T temperature of the p-n junction.

1.1. Effect of Irradiation on PV Cell Characteristics

Solar module efficiency indeed depends on the input variable irradiance, as varying irradiance levels affect the output efficiency of the module. As irradiance increases, the number of incident photons on the module also increases. This leads to higher power output and increased efficiency. The relationship between irradiance and short circuit current is linear (i.e., the short circuit current increases proportionally with the increase in irradiance level). Similarly, as irradiance increases, the open circuit voltage also increases.
As shown in Figure 2, the effect of irradiance on the open circuit voltage is not as significant as its effect on the short circuit current [14].

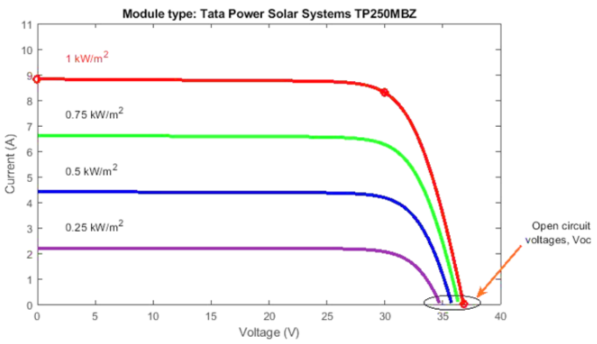

Fig. 2. I-V curves of different irradiance levels

1.2. PSO Algorithm

PSO algorithm is a swarm technique that is inspired by the collective behaviour of social insect colonies and other animal societies [11, 15–19]. The PSO drives each particle throughout the search space, updating the best solution based on each particle's neighbouring experience. The PSO starts by randomly initializing particles, then searching for optimum solutions through iteration, and then evaluating the solution quality with a fitness function. The PSO algorithm is efficient in searching global optimum with high accuracy.

The particle position is influenced by the position of the best particle in a neighbourhood. The particle position is modified using [9]:

$$X_i^{t+1} = X_i^t + V_i^{t+1} \quad (8)$$

The step size is represented by the velocity component, V_i. The velocity is determined using the formula

$$V_i^{t+1} = w.V_i^t + c_1r_1(P_{best_i} - X_i^t) + c_2r_2(g_{best_i} - X_i^t) \quad (9)$$

$$i = 1,2,\dots,n$$

i represents the variable to be optimized, t is the number of iterations, V_i^t and X_i^t are velocity and position of the ith variable within k iterations, P_{best_i} records the personal best position of the ith variable, g_{best_i} records the global best position in the swarm, w is the inertia of the particle, c_1 cognitive coefficient of individual particles, c_2 is the social coefficient of all particles, $r_1\&r_2$ are random numbers (0,1) of size (1 X D) where D is the number of decision variables.

1.3. Flowchart of a Basic PSO

Provide the inertia(w), acceleration coefficient ($c_1\&c_2$) and population size.
Step 1: Initialize the population of particles with X positions and V velocities.
Step 2: Initialize t=1.
Step 3: Send the candidate solution to the objective function to evaluate each particle's fitness.
i.e. $f_i^k = f(X_i^k), \forall_i$.
Step 4: Update P_{best_i} and g_{best_i}
Step 5: Each particle's position and velocity should be updated.
Step 6: Reinitialize the PSO algorithm until constraints are met.

1.4. Duty Cycle Computation for DC-DC Converter

Given that a DC-DC converter's output voltage stays constant, the PV voltage (i.e. input voltage) may be determined using the DC-DC converter's output voltage V_o and the duty cycle d. The conventional controller duty cycle is generated as follows (Alshareef et al., 2019):

$$d = 1 - \frac{V_{in}}{V_o} \quad (10)$$

The particle's position X_i^t is defined as the duty cycle d_i^t of the duty cycle to apply the aforementioned equation to the PSO algorithm in PV systems. In addition, the change in the duty cycle Δd_i^t is defined as the particle velocity V_i^k. The PSO velocity and position updating equations can be written as:

$$\Delta d_i^{t+1} = w.\Delta d_i^t + c_1r_1(P_{best_i} - d_i^t) + c_2r_2(g_{best_i} - d_i^t) \quad (11)$$

$$d_i^{t+1} = d_i^t + \Delta d_i^{t+1} \quad (12)$$

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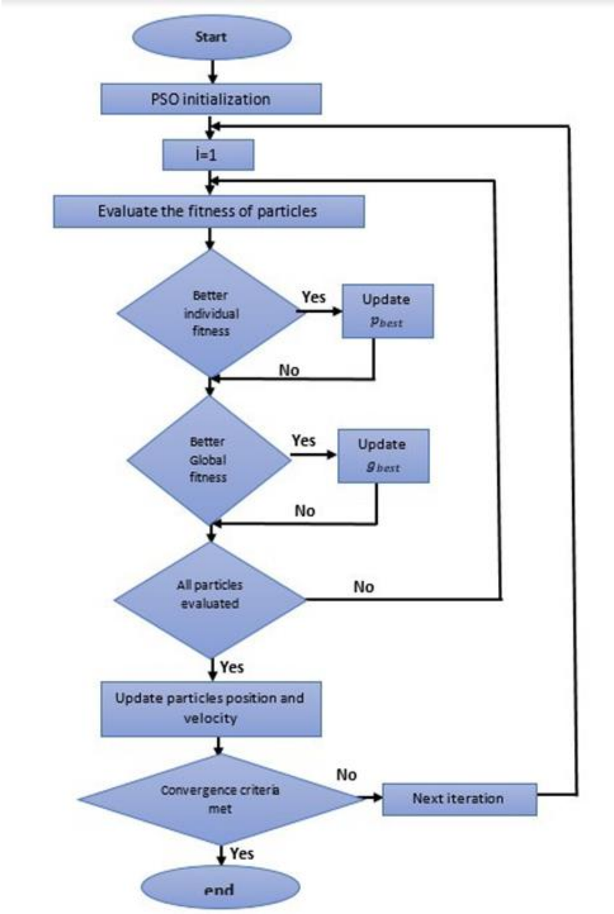

Fig. 3. Flowchart of a standard PSO

2. Proposed PSO Algorithm

The PSO method is applied to realize the photovoltaic MPPT algorithm under partial shading conditions. The P-V curves give multiple local maximum power points and a modification of the standard PSO is implemented. A series-connected PV module, a DC-DC converter to interface the voltage from the PV module to the load, a digital controller (MPPT controller), and a load are shown in the block diagram.

Fig 4 illustrates the suggested PSO-based MPPT technique's flowchart. The main blocks are presented in the stages that follow.

Step 1 (Selection of parameter): In the proposed systems, four particles are transmitted. The duty cycle d of the DC-DC converter represents the particle position. The generated power P_{pv} is defined as the fitness value function.

Step 2 (Initialization of PSO): Particles can be deployed in a set position or randomized in space using the PSO method. The particle can also be initialized around a known GMPP (Patel & Agarwal, 2008). The particles are initialized on predetermined positions in this study, which cover the search space $D_{min,}\ and\ D_{max}$, that represent the converter's maximum and minimum duty cycles, respectively. 0 and 0.95 were chosen as the values. In addition, the particle velocities are set to positions that are dependent on $D_{min,}\ and\ D_{max}$. The fixed velocities are given in equation:

$$V_{max} = 0.6\ {}^{(D_{max} - D_{min})}/_{2} \quad (13)$$

$$V_{min} = -1. V_{max} \quad (14)$$

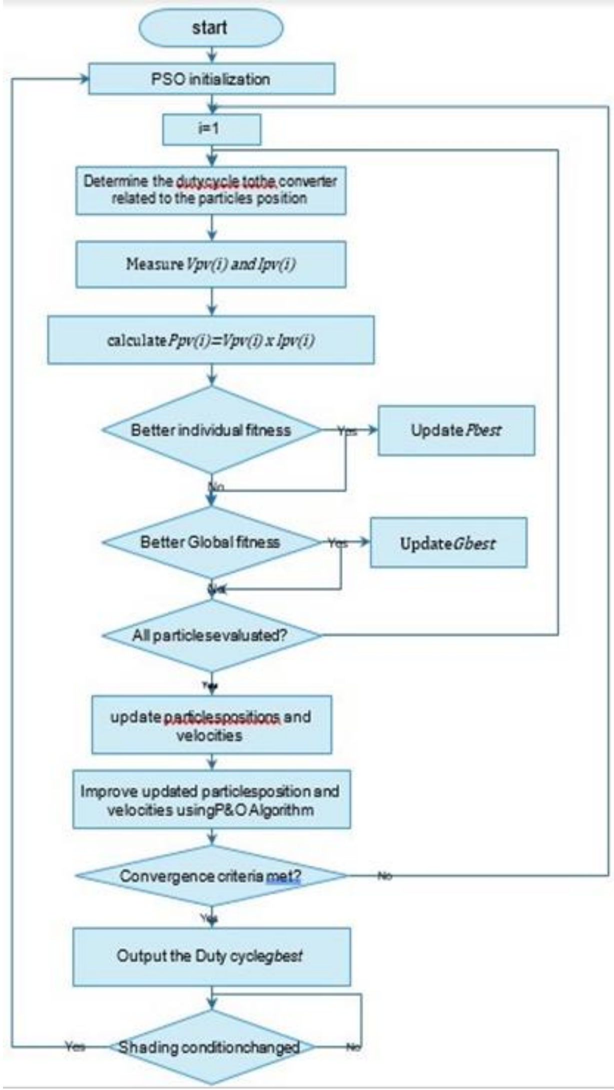

Fig. 4. Proposed PSO-based MPPT technique

Step 3 (Evaluation of fitness): The PV voltage and current are sensed and computed to obtain the PV output power. These variables can be used to evaluate the ith particle's fitness value P_{PV}.

Step 4 (Update personal and global best solutions): Particle with a fitness value better than the fitness value in memory of $P_{best,i}$ is set as the new $P_{best,i}$. Also, the particle with the best fitness value of all the particles is set to be the new g_{best}. This is obtainable in the conventional PSO technique.

Step 5 (Update velocity and position of each particle): The new velocities and positions of all particles are updated after being evaluated. In a standard PSO method, the update for velocities and positions are computed using equation (11)

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and equation (12) respectively. In addition, as the velocity approaches Gbest in traditional PSO-based MPPT algorithms, the velocity decreases. In this paper, the maximum velocity and maximum duty cycle are perturbed after being updated with the conventional PSO algorithm. This is implemented by comparing the updated values with the old values of V_{max} and V_{min}. To attain a faster convergence time, the P&O method is also employed to improve the updated value.

Step 6 (Convergence Evaluation): In this article, two convergence criteria are used. The algorithm outputs the obtained g_{best} solution if all particle velocities fall below a certain threshold or if the maximum number of iterations is reached.

Step 7 (Re-initialization): Re-initialize particles when there is a variation in environmental conditions. In this paper equation (15) is used to detect environmental changes and the PSO will reinitialize [16].

$$\frac{|P_{pv,new}-P_{pv,past}|}{P_{pv,past}} > \Delta P(\%) \tag{15}$$

3. System Arrangement

MATLAB was used to verify the performance of the modified PSO algorithm. The model is designed on MATLAB/Simulink R2020b as shown in Fig 5a which includes 4 series connected PV panels as shown in Fig 5b. Table 1 provides the parameters of the PV module that was employed. The four PV cells were exposed to varied levels of irradiation. MATLAB was used to run all the simulations. Table 2 lists the parameters of the proposed PSO algorithm. An arbitrary set of insolation of series-connected PV cells is used to simulate the effect of partial shading conditions on characteristic curves. The simulation was performed using three different GMPP and LMPP P-V and I-V characteristic curves as in [20], [22], [23]. The cell temperature was made constant (i.e. 25°C) for the entire simulation. The cell that is not shaded is considered to be at its maximum at 1000w/m^2.

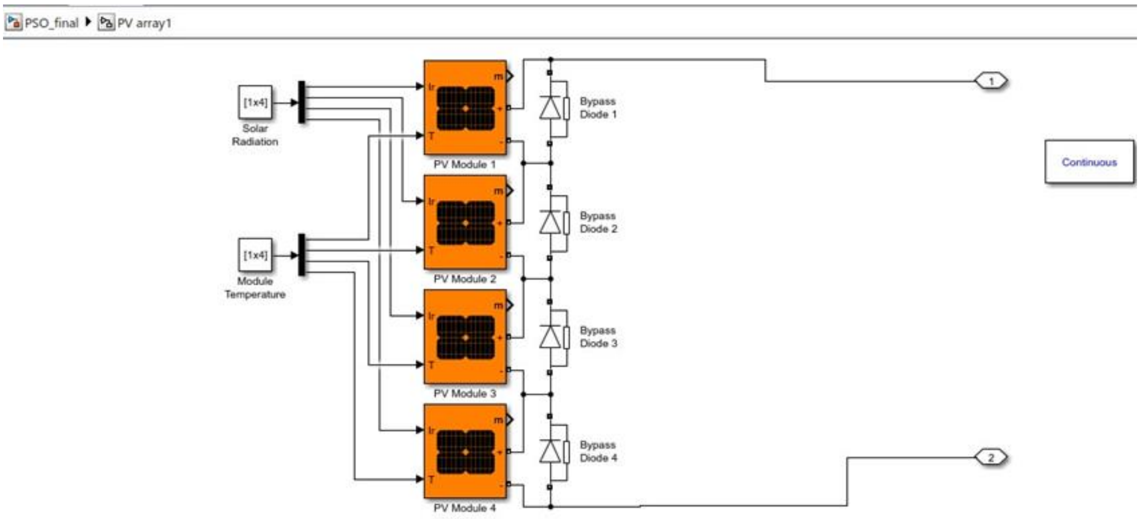

Fig. 5(a). Model of series-connected PV arrays

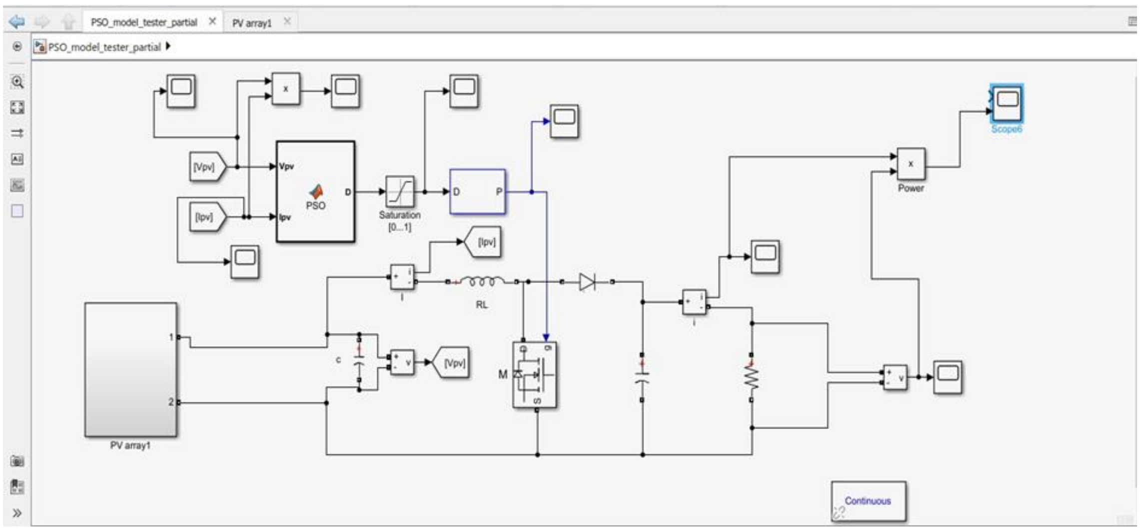

Fig .5(b). Model of the PV systems implemented

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Table 1. Parameters for a single PV module

Module type	Tata Power Solar Systems TP250MBZ
Max. Power (Pmax)	249w
Open circuit Voltage (Voc)	36.8v
The voltage at Max. power (Vmp)	30v
Short circuit current (Isc)	8.83A
Current at Max. power (Imp)	8.3A
Temperature coefficient (αv)	-0.33
Cells per module (Ncell)	60
Configuration	4s

Table 2. Parameter of the proposed PSO algorithm

Number of particles	4
Min. duty cycle, (d_{min})	0
Max. duty cycle, (d_{max})	0.95
Max. iteration	30
W	0.4
C1	1.2
C2	2
V_{max}	$0.6(d_{max} - d_{min})/2$
V_{min}	$-1 * V_{max}$

4. Simulation Results under Different Environmental Conditions

Three (3) different patterns of environmental conditions were introduced to the system to evaluate the suggested PSO algorithm. The patterns are characterized by the output power, and they are the average values of all PV modules in the system. The performance was compared with the literature found in [20], [22]. In simulations, the values of voltage and current are computed through the scope reading.

Pattern 1

In the first pattern, the system was subjected to different irradiance levels as given in Table 3. The PV output has three maximum power points with GMPP located in the middle. Fig 6 shows the P-V and I-V properties of GMPP and LMPP. Fig 6 shows that the GMPP was obtained at a power value of P=637.944w. Fig 7(a-c) depicts the voltage current, duty cycle, and power simulation waveform.

Table 3. Irradiation level for the first pattern

PV module	Irradiance(w/m^2)
PV 1	500
PV 2	800
PV 3	1000
PV 4	1000

The suggested PSO model was considered to reach the GMPP in 1.086s with a PV output power of 636.3V. The traditional PSO algorithm took longer to get to GMPP (i.e. 4.6s). In addition, the accelerated PSO algorithm took 3.2s to reach GMPP and in [20] 2.4s to reach GMPP it took 3.2s to reach GMPP and 2.4s the accelerated PSO algorithm to reach GMPP.

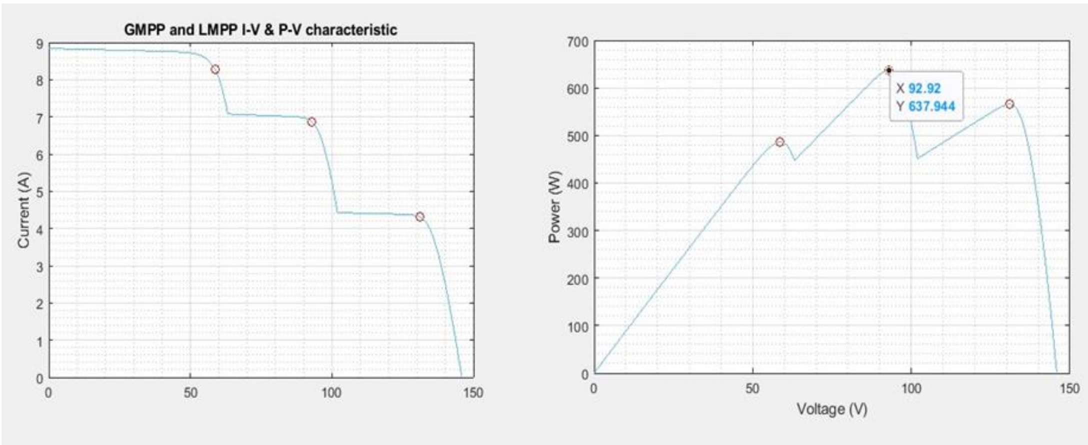

Fig. 6. GMPP and LMPP I-V and P-V characteristic curves of the first pattern

Pattern 2

In the second pattern, the system was subjected to different irradiance levels as given in Table 4. The PV output has three maximum power points with GMPP located on the right side. Fig 8 shows the GMPP and LMPP P-V and I-V characteristics curves. The GMPP was obtained at power value, P=527.6w as shown in Fig 8. The simulation waveform of the voltage-current, duty cycle, and power are shown in Fig 9(a-c).

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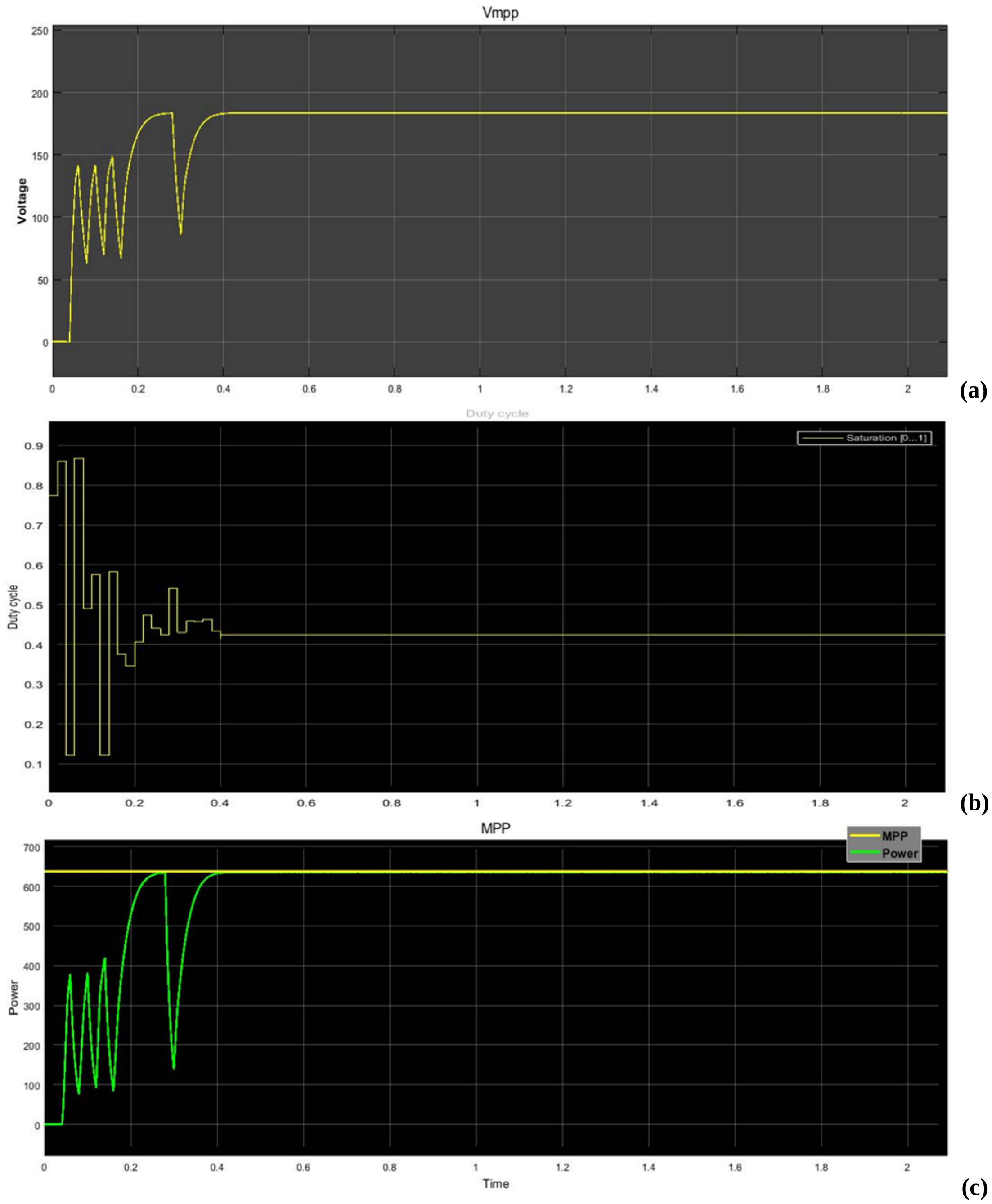

Fig. 7. Simulation results of the first pattern for the proposed PSO algorithm: (a) Voltage, (b) Duty cycle (c) Power

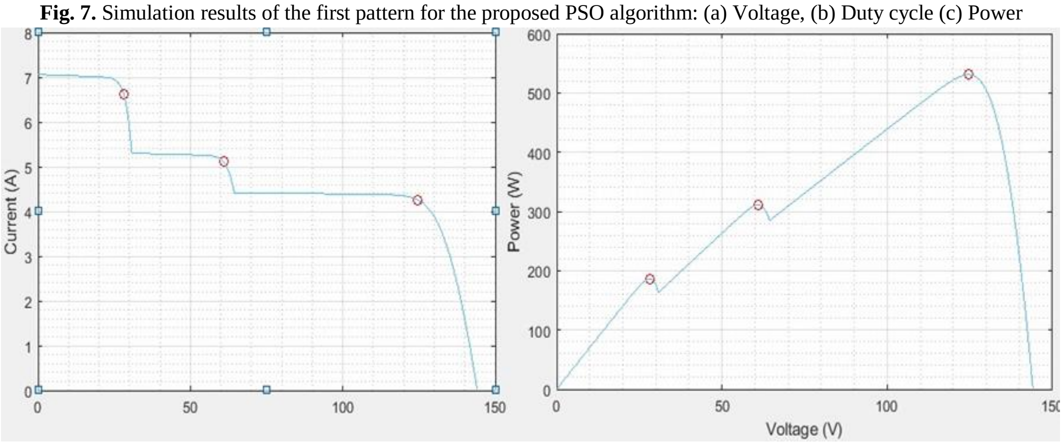

Fig. 8. GMPP and LMPP I-V and P-V characteristic curves of the second pattern

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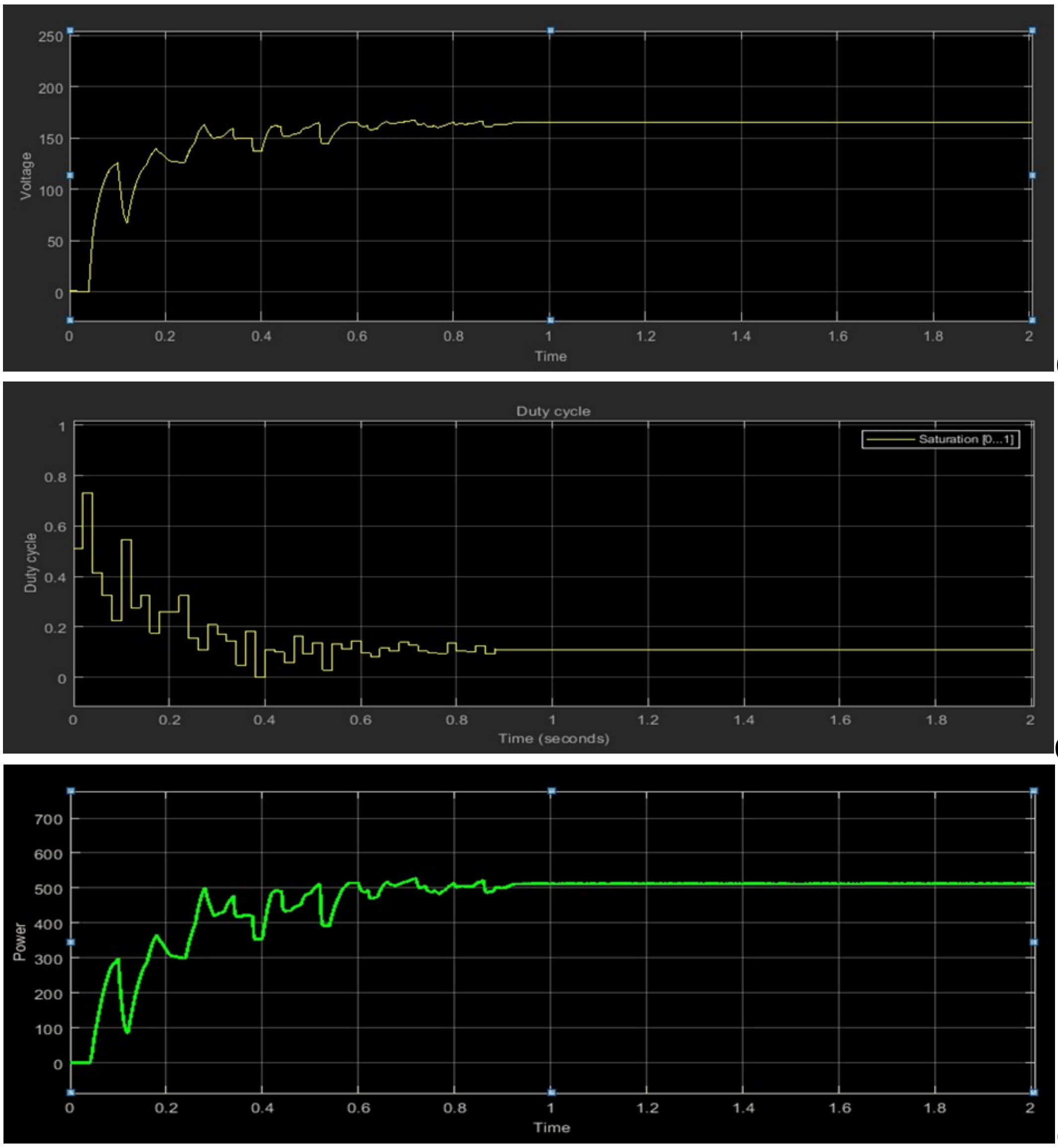

(a)
(b)
(c)

Fig. 9. Simulation results of the second pattern for the proposed PSO algorithm: (a) Voltage, (b) Duty cycle (c) Power

Table 4. Irradiation level for the second pattern

PV module	Irradiance(w/m^2)
PV 1	800
PV 2	600
PV 3	500
PV 4	500

The suggested PSO algorithm was found to attain the GMPP in 0.99s with a PV output power of 518.27V. The traditional PSO algorithm took longer to get to GMPP (i.e. 4.2s). In addition, the accelerated PSO method took 2.3s to reach GMPP and 3.2s in [20].

Pattern 3

In the third pattern, the system was subjected to different irradiance levels as given in Table 5. The PV output has two maximum power points with GMPP located on the left side. Fig 10 shows the P-V and I-V properties of GMPP and LMPP. As indicated in Fig 10 from the power(w) axis, the GMPP was obtained at a power of P=741.167W. Fig 11(a-d) depicts the voltage current, duty cycle, and power simulation waveform.

The suggested PSO method reached the GMPP in 0.83s with a PV output power of 740.3w. The traditional PSO algorithm took longer to get to GMPP (i.e. 4.2s). In addition, the accelerated PSO method took 3.2s to reach GMPP [20], while the standard PSO approach took 2.3s.

Table 5. Irradiation level for the third pattern

PV module	Irradiance(w/m^2)
PV 1	1000
PV 2	1000
PV 3	1000
PV 4	400

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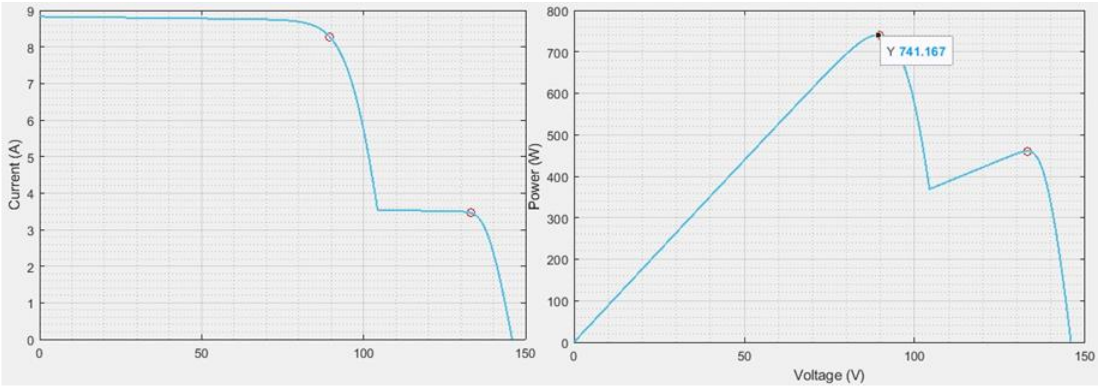
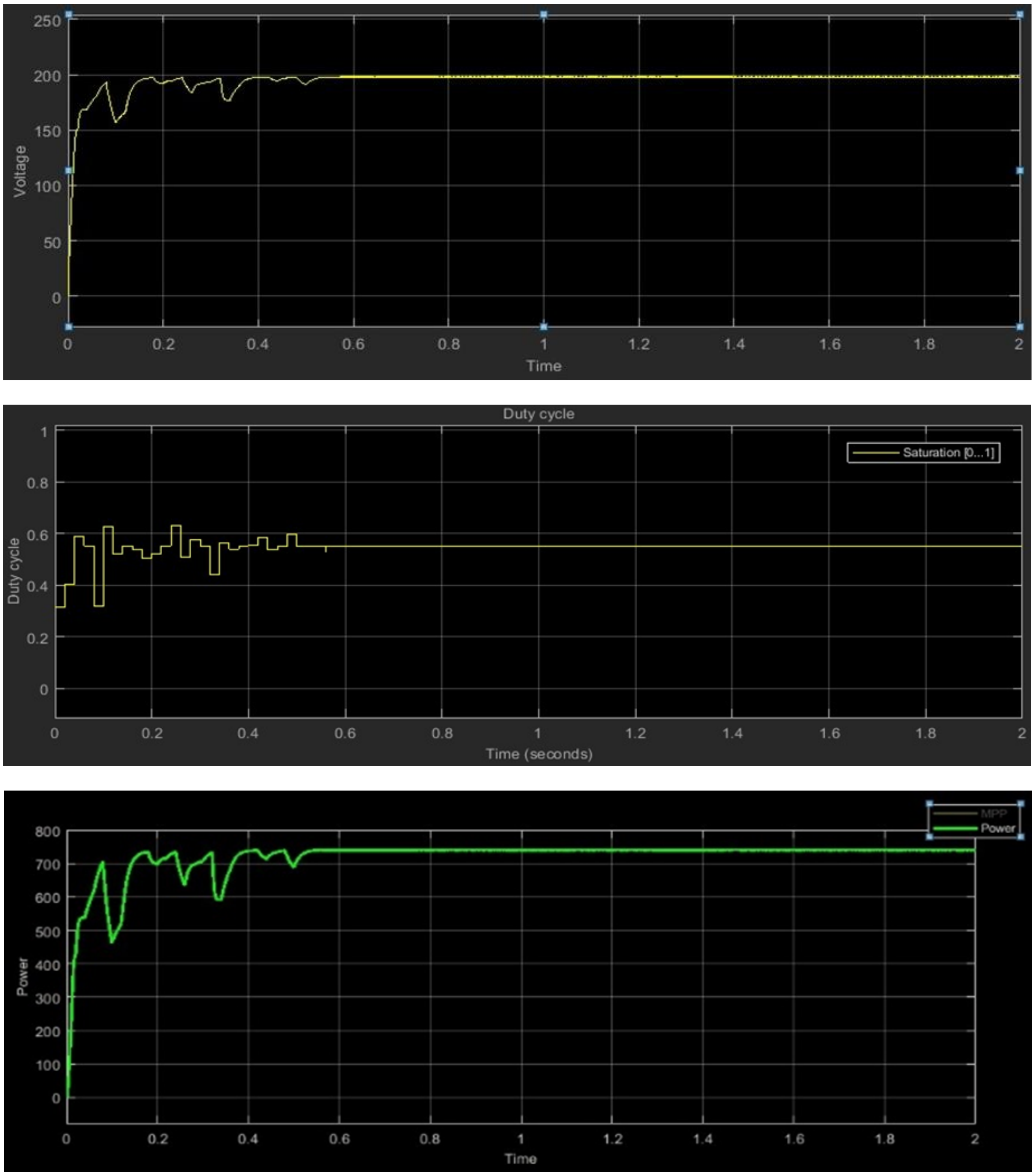


Fig. 10. GMPP and LMPP I-V and P-V characteristic curves of the third pattern



(a)

(b)

(c)

Fig. 11. Simulation results of the third pattern for the proposed PSO algorithm: (a) Voltage, (b) Duty cycle (c) Power

5. Discussion

It is known that the performance of conventional MPPT technology exceeds 99% under continuous sun exposure [24]. However, in the case of partial shading, the accuracy of these MPPT techniques is reduced due to multiple local maxima. The inaccuracy of conventional MPPT techniques under PSC can be seen in Fig 12. In this scenario, the actual MPP is at point C, but the power point moves to point B. However, with the traditional method like P&O, the duty points change according to the prescribed voltage command step (v) and the duty point oscillates around the B point. Power losses are also seen between Pc and Pb points. To avoid this performance degradation, MPPT should be moved to operating point C. The proposed MPPT techniques consider the disadvantages of conventional models.

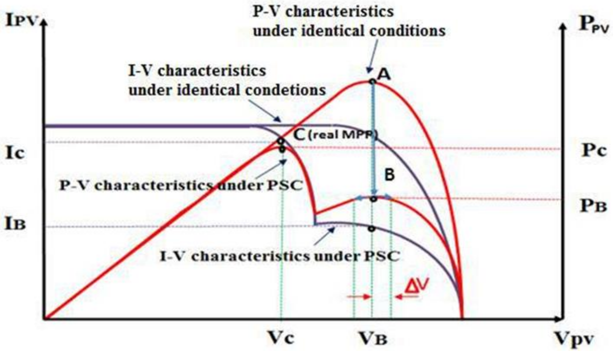


Fig 12. P-V and I-V characteristics of PV cells under shaded and unshaded conditions [25]

Three different patterns were used to evaluate the proposed algorithm and compare it with other MPPT algorithms under various shading conditions. Models 1, 2, and 3 have three MPP outputs and GMPP occurs at medium, highest, and lowest voltage respectively. It was noticed that the proposed algorithm reached GMPP 1.068, 0.95s, and 0.83 with steady-state accuracy of 99.8%, 98%, and 99.8% respectively. The measured MPPT accuracy is calculated from the two steady-state power values and the MPP in each sample. The conventional PSO took more than 3.2 seconds and had 98% accuracy in cases 1 and 2 while in case 3 it had 96% accuracy with a reduced tracking time of 2.8 seconds. Also, APSO took 2.4, 2.3, and 1.9 seconds to reach GMPP with 99.5%, 99%, and 99% accuracy, respectively. As a result of the simulation, the proposed algorithm converges faster than the standard PSO algorithm and obtains better accuracy.

However, it performed well when compared to other PSO-based MPPT techniques. It is seen that the average accuracy and tracking time of the proposed method based on steady-state balance metrics are 99.2% and 0.94s, with the PSO algorithm [22] it is 98% and 3.075s, 96.6%. and 99.17% and 2.2s for the PSO algorithm [20] and APSO [20] algorithm with 3.975s. The reduction in watch time is associated with the P&O technique as it is used to update the Global best. This moves Gbest to a higher fitness level and attracts other particles to converge to GMPP in less time. Therefore, due to the integration of PSO and P&O techniques, this technique performed better in terms of accuracy and tracking time.

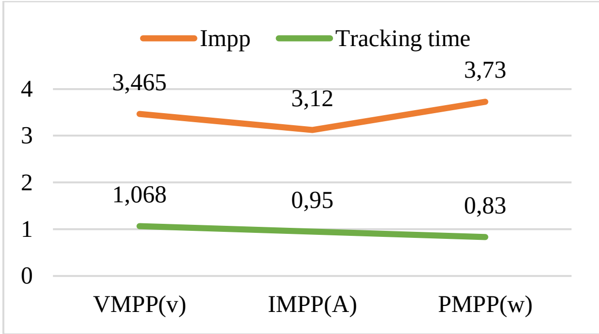


Fig 13. Impp and tracking time of the model

6. Conclusion

In this paper, a PSO-MPPT technique was proposed, implemented, and simulated in MATLAB/Simulink to track the global MPP for a PV system under partial shading. Using the P&O technique, the suggested PSO incorporated a perturbing step. The modified Vmax and Dmax were further enhanced using the P&O algorithm. This change is based on GMPP tracking with faster convergence and accuracy in tracking.

Table 6 summarizes the results of a comparison. The algorithm has been validated by simulating 3 different shading patterns in MATLAB. Models 1 and 2 have three MPP outputs, and GMPP occurs at medium voltage, the highest voltage, and the lowest voltage, respectively. It is noticed that the proposed algorithm reaches GMPP 1.068 and 0.95s with steady-state accuracy of 99.8% and 98%, respectively. The measured MPPT accuracy is calculated from two steady-state power values and each steady-state MPP. Conventional PSO provided more than 3.2 seconds and 98% accuracy in both cases. Also, APSO took 2.4 and 2.3 seconds to reach GMPP with 99.5% and 99% accuracy, respectively. As a result of the simulation, the proposed algorithm converges faster than the standard PSO algorithm and obtains better accuracy.

The results show that the algorithm can accurately monitor GMPP from local MPPs. It also has a faster convergence time when compared, to other MPPT algorithms.

The proposed technique has the following advantage.

1. The tracking accuracy of GMPP is very high compared to other methods.
2. With the introduction of the P&O technique, it converges faster than other methods.
3. It is suitable in all irradiation configurations, especially in varying weather and shading conditions.

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Table 6. Summary of comparison results of different PSO methods

Shading pattern	Technique	V at max power(v)	I at max power(A)	P_{mpp}(w)	Rated Power(w)	Eff. (%)	Tracking time(s)
Pattern 1	Proposed	183.6	3.465	636.3	637.7	99.8	1.068
	PSO [22]	23.45	1.72	40.37	40.76	99	3.2
	PSO [20]	22.55	1.75	39.44	40.76	97	4.6
	APSO [20]	23.54	1.72	40.56	40.76	99.5	2.4
Pattern 2	Proposed	165.8	3.12	518.27	527.6	98	0.95
	PSO [22]	21.95	3.48	76.39	76.53	99	3.2
	PSO [20]	22.07	3.27	72.17	76.53	94	4.3
	APSO [20]	22.01	3.47	76.51	76.53	99	2.3
Pattern 3	Proposed	198.03	3.73	740.3	741.18	99.8	0.83
	PSO [22]	31.44	2.23	70.31	73.62	96	2.8
	PSO [20	31.54	2.3	73.33	73.62	99	3
	APSO [20]	31.54	2.32	73.33	73.62	99	1.9

Authorship contribution statement for Contributor Roles Taxonomy

Al-amin Yakubu: Writing - original draft, Investigation, Visualization, Conceptualization, Methodology, Software, Formal analysis. **Ertugrul Adiguzel:** Investigation, Supervision, Writing – review & editing. **Aysel Ersoy:** Investigation, Visualization, Supervision.

Conflict of interest

We declare that there is no conflict of interest in this article.

References

[1] M. A. Alrikabi, "Renewable Energy Types," *J. Clean Energy Technol.*, vol. 2, no. 1, pp. 61–64, 2014.

[2] K. Sarah, "A Review of Solar Photovoltaic Technologies." *International Journal of Engineering Research and Technology.* Vol. 9. Issue 7, pp. 741-749, 2020.

[3] T. Esram and P. L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," *IEEE Trans. Energy Convers.*, vol. 22, no. 2, 2007.

[4] K. Sundareswaran, V. Vigneshkumar, P. Sankar, S. P. Simon, P. Srinivasa Rao Nayak, and S. Palani, "Development of an Improved P&O Algorithm Assisted Through a Colony of Foraging Ants for MPPT in PV System," *IEEE Trans. Ind. Informatics*, vol. 12, no. 1, 2016.

[5] H. Patel and V. Agarwal, "MATLAB-based modeling to study the effects of partial shading on PV array characteristics," *IEEE Trans. Energy Convers.*, vol. 23, no. 1.

[6] A. soufyane Benyoucef, A. Chouder, K. Kara, S. Silvestre, and O. A. Sahed, "Artificial bee colony-based algorithm for maximum power point tracking (MPPT) for PV systems operating under partial shaded conditions," *Appl. Soft Comput. J.*, vol. 32, 2015.

[7] R. Sridhar, S. Jeevananthan, N. T. Selvan, and S. Chowdary, "Performance improvement of a photo voltaic array using MPPT (P&O) technique," 2010.

[8] B. Liu, S. Duan, F. Liu, and P. Xu, "Analysis and improvement of maximum power point tracking algorithm based on incremental conductance method for photovoltaic array," 2007.

[9] A. P. Engelbrecht, *Computational Intelligence: An introduction*. New Jersey: John Wiley and Sons Ltd, 2002.

[10] Y. H. Liu, S. C. Huang, J. W. Huang, and W. C. Liang, "A particle swarm optimization-based maximum power point tracking algorithm for PV systems operating under partially shaded conditions," *IEEE Trans. Energy Convers.*, vol. 27, no. 4, 2012.

[11] P. Kotecha, "Particle Swarm Optimization," National Programme on Technology Enhanced Lerning, 2020.

[12] A. Musa, "A modified Particle Swarm Optimization Based Maximum Power Point Tracking for Photovoltaic Converter System," University of Technologi Malaysia, 2015.

[13] L. Umanand, "Design of photovoltaic systems," Indian Institue of Science, Banalore, NPTEL Online Certificate Course, 2018.

[14] D. Leitão, J. P. N. Torres, and J. F. P. Fernandes, "Spectral irradiance influence on solar cells efficiency," *Energies*, vol. 13, no. 19, 2020.

[15] J. C. Bansal, P. K. Singh, M. Saraswat, A. Verma, S. S. Jadon, and A. Abraham, "Inertia weight strategies in particle swarm optimization," 2011.

[16] K. Ishaque, Z. Salam, H. Taheri, and A. Shamsudin, "Maximum Power Point Tracking for PV system under partial shading condition via particle swarm optimization," 2011.

[17] H. Chaieb and A. Sakly, "A novel MPPT method for photovoltaic application under partial shaded conditions," *Sol. Energy*, vol. 159, 2018.

[18] A. P. Engelbrecht, "Chapter 16 - Particle Swarm Optimization," *Comput. Intell. An Introd.*, 2007.

[19] S. Sreedhar and D. Jagadeesh, "A Review on Optimization Algorithms for MPPT in Solar PV System under Partially Shaded Conditions," no. January 2016, pp. 23–32, 2016.

[20] M. Alshareef, Z. Lin, M. Ma, and W. Cao, "Accelerated particle swarm optimization for photovoltaic maximum power point tracking under partial shading conditions," *Energies*, vol. 12, no. 4, 2019.

[21] H. Patel and V. Agarwal, "Maximum power point tracking scheme for PV systems operating under partially shaded conditions," *IEEE Trans. Ind. Electron.*, vol. 55, no. 4, 2008.

[22] S. Rajendran and H. Srinivasan, "Simplified accelerated particle swarm optimization algorithm for efficient maximum power point tracking in partially shaded photovoltaic systems," *IET Renew. Power Gener.*, vol. 10, no. 9, 2016.

[23] W. Hayder, E. Ogliari, A. Dolara, A. Abid, M. Ben Hamed, and L. Sbita, "Improved PSO: A comparative study in MPPT algorithm for PV system control under partial shading conditions," *Energies*, vol. 13, no. 8, 2020.

[24] Eberhart and Yuhui Shi, "Particle swarm optimization: developments, applications, and resources," Proceedings of the 2001 Congress on Evolutionary Computation (IEEE Cat. No.01TH8546), 2001, pp. 81-86 vol. 1.

[25] S. Sreedhar and D. Jagadeesh, "A Review on Optimization Algorithms for MPPT in Solar PV System under Partially Shaded Conditions," IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE) e-ISSN: 2278-1676, pp 23-32, 2016.

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