International Journal of Electrical and Computer Engineering (IJECE)
Vol. 12, No. 5, October 2022, pp. 4559~4570
ISSN: 2088-8708, DOI: 10.11591/ijece.v12i5.pp4559-4570

Tunicate swarm algorithm based maximum power point tracking for photovoltaic system under non-uniform irradiation

Evi Nafiatus Sholikhah, Novie Ayub Windarko, Bambang Sumantri
Department of Electrical Engineering, Politeknik Elektronika Negeri Surabaya, Surabaya, Indonesia

Article Info

Article history:

Received Jun 15, 2021
Revised Apr 20, 2022
Accepted May 15, 2022

Keywords:

DC-DC buck converter
Maximum power point tracking
Non-uniform irradiation
Photovoltaic system
Tunicate swarm algorithm

ABSTRACT

A new maximum power point tracking (MPPT) technique based on the bio-inspired metaheuristic algorithm for photovoltaic system (PV system) is proposed, namely tunicate swarm algorithm-based MPPT (TSA-MPPT). The proposed algorithm is implemented on the PV system with five PV modules arranged in series and integrated with DC-DC buck converter. Then, the PV system is tested in a simulation using PowerSim (PSIM) software. TSA-MPPT is tested under varying irradiation conditions both uniform irradiation and non-uniform irradiation. Furthermore, to evaluate the performance, TSA-MPPT is compared with perturb & observe-based MPPT (P&O-MPPT) and particle swarm optimization-based MPPT (PSO-MPPT). The TSA-MPPT has an accuracy of 99% and has a reasonably practical capability compared to the MPPT technique, which already existed before.

Corresponding Author:

Evi Nafiatus Sholikhah
Department of Electrical Engineering, Politeknik Elektronika Negeri Surabaya
Raya ITS St., Surabaya City, East Java 60111, Indonesia
Email: evinafiatus30@mail.com

1. INTRODUCTION

The installation of photovoltaic (PV) modules arranged in series-parallel to form PV arrays for solar power generation has grown quite fast in recent years. The electrical energy produced by the PV array is very dependent on environmental conditions, such as solar irradiation and temperature [1]. One of the factors that affect solar irradiation is partial shading conditions. Partial shading is a condition where the PV array is partially covered by dust accumulation, building shadows, tree shadows, or clouds. It causes the PV array to receive non-uniform irradiation. In addition, some of the PV arrays covered in shadows will be energized by the current generated by the PV arrays that are not covered in shadows. So, the power generated by the PV array will decrease significantly compared to uniform irradiation conditions. This condition will also increase the PV module temperature, causing a hotspot on the PV module, so the degradation of the PV module will accelerate. To reduce the effect of partial shading is to install a bypass diode on each PV module. As a result of the installation of this bypass diode, the PV array characteristics have several power peaks, namely global maximum power point (GMPP) and local maximum power point (LMPP) [2]–[4].

One solution to increase the PV array output power efficiency is the maximum power point tracking (MPPT) technique to track the PV array maximum power. The MPPT technique consists of an algorithm implemented into a microcontroller system integrated with a power converter and sensors. The implemented algorithm is used to determine the duty cycle, which is then used to control the switching of the power converter. The MPPT technique has developed quite rapidly in recent years, with various algorithms classified into conventional algorithms and soft computing algorithm that can track maximum power points under uniform irradiation and non-uniform irradiation conditions [5]–[7].

In the existing works, MPPT with conventional algorithms such as perturb & observe-based MPPT (P&O-MPPT) is not sufficient to track GMPP with non-uniform irradiation [8]. Therefore, as an alternative, the soft computing algorithm is implemented as an algorithm in the MPPT technique. The bio-inspired metaheuristic algorithm based MPPT has a practical ability to track GMPP both of uniform and non-uniform irradiation conditions [9]. Several MPPT techniques based on bio-inspired metaheuristic algorithms include particle swarm optimization-based MPPT (PSO-MPPT) [10], flower pollination algorithm-based MPPT (FPA-MPPT) [11], grey wolf optimization-based MPPT (GWO-MPPT) [11], artificial bee colony-based MPPT (ABC-MPPT) [12], ant colony optimization-based MPPT (ACO-MPPT) [13], human psychology optimization-based MPPT (HPO-MPPT) [14], grass hopper optimization-based MPPT (GHO-MPPT) [15], and cuckoo search optimization-based MPPT (CSO-MPPT) [16]. The advantage of the bio-inspired metaheuristic algorithm is that it can track GMPP in both non-shading conditions with uniform irradiation and partial shading conditions with non-uniform irradiation. The fundamental differences between the algorithms include the speed of convergence, the range of effectiveness, control parameters, the level of design complexity, the sensors used, and the cost of hardware implementation [17]–[19].

In 2020, a new bio-inspired metaheuristic algorithm, namely the tunicate swarm algorithm (TSA) was firstly proposed by Kaur *et al*. This algorithm can solve global optimization problems, both based on unimodal and multimodal functions. The TSA algorithm has an effective performance from the performance evaluation results compared to the eight bio-inspired metaheuristic algorithms that have existed before [20]. The advantage of the TSA algorithm is that it has a very simple mathematical modelling so that it is easy to implement on many systems. Several examples of TSA algorithm implementation are used as parameter extraction in PV modules [21] and optimal control and operation of fully automated distribution networks [22].

From the background, this paper purposes to design and implement the tunicate swarm algorithm based MPPT (TSA-MPPT). The proposed algorithm is implemented on a DC-DC Buck converter, integrated with a PV array consisting of 5 PV modules connected in series and integrated with a voltage sensor and current sensor. Furthermore, the system is simulated using PSIM 9.1.1. In addition, for performance evaluation, the TSA-MPPT is compared with P&O-MPPT and PSO-MPPT. The TSA algorithm has the advantage of being relatively easy to implement and can track both uniform and non-uniform irradiation conditions. This paper is organized into four sections. Introduction in section 1. The research methods, including PV module modeling, DC-DC Buck converter modeling, and the TSA algorithm described in section 2. Then, the results and analysis are described in section 3 and the conclusion is in section 4.

2. RESEARCH METHOD

2.1. PV module modelling

Figure 1 shows an equivalent circuit of single diode PV cell model. This model is represented by a parallel current source with parallel diode and resistor and a series of resistor connected at the output terminals [23]. According to the single diode PV cell model, the I-V characteristics of the PV module are formulated by (1).

$$I_{pv} = I_{ph} - I_s\left(e^{\frac{V_{pv}+I_{pv}R_S}{nN_sV_t}} - 1\right) - \frac{V_{pv}+I_{pv}R_S}{R_{sh}} \quad (1)$$

I_{pv} and V_{pv} are the PV module output current and PV module output voltage. I_{ph} is the photovoltaic current, I_s is the saturation current, R_s is the series resistor, R_{sh} is the parallel resistor, n is the diode quality factor, N_s is the number of PV cells connected to the PV module, and V_t is the thermal voltage of the PV cells defined as $V_t = {}^{kT}/_{q}$, where k is Boltzmann's constant (1.38×10^{-23} J/K), q is the elementary charge (1.6×10^{-19} C), and T is p-n junction temperature in Kelvin.

2.2. PV array characteristic

To produce large electrical power, PV modules are arranged to form a PV array. The amount of power generated by the PV array is highly dependent on the amount of solar irradiation. The higher the solar irradiation, the greater the power that the PV array can generate. PV arrays have identical characteristics with PV modules. PV array have non-linear characteristics, which is usually represented using I-V curves and P-V curves. Where every change in irradiation conditions, the PV array will have a maximum power point (MPP) called the global maximum power point (GMPP). In this paper, 5 PV modules are connected in series as shown in Figure 2(a) where the PV module parameters used are listed in Table 1.

In non-shading conditions with uniform irradiation, the characteristic of the PV array has one GMPP as shown in the orange curve in Figure 2(b). While in partial shading conditions with non-uniform irradiation as shown in the yellow and green curves in Figure 2(b), the PV array produces several MPP peaks as a result of installing bypass diodes in the PV array circuit and a significant decreasing in power occurs due to losses in the form of heat. From the several MPP peaks, there is only one MPP which is the correct MPP peak or is called GMPP while the other MPP point is called LMPP. The number of MPPs depends on the topology of the PV array used and the partial shading conditions [2].

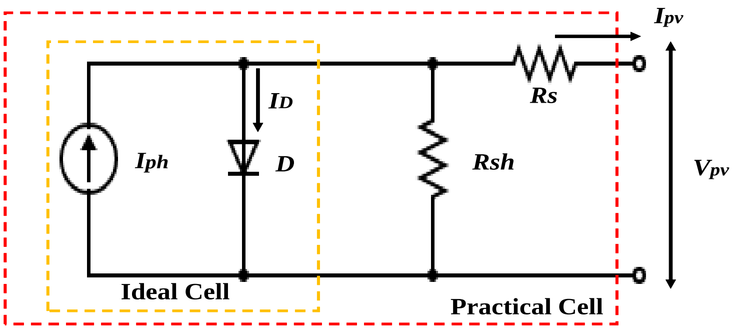
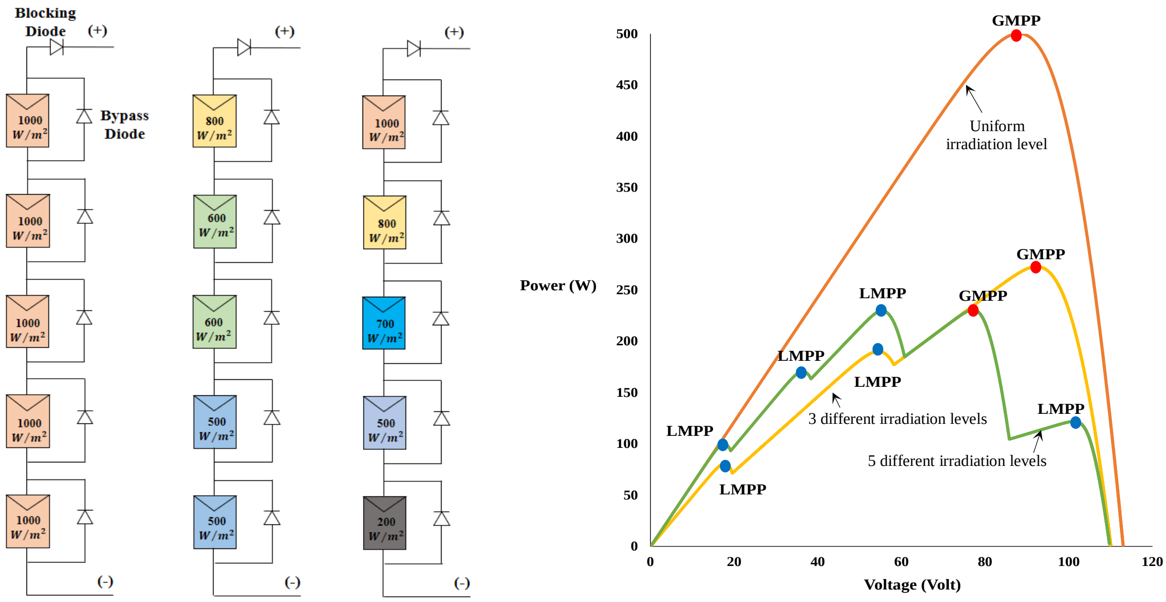


Figure 1. The equivalent circuit of single diode PV cell model [23]



(a) (b)

Figure 2. PV Array (a) PV modules connected in series and (b) PV array characteristic

Table 1. The PV module parameters

No.	Parameter	Variable	Value
1	Number of cells	N_s	36
2	Maximum Power	P_m	100 W
3	Voltage at Pm	V_m	17.6 V
4	Current at Pm	I_m	5.68 A
5	Open Circuit Voltage	V_{oc}	21.8 V
6	Short Circuit Current	I_{sc}	6.09 A
7	Shunt Resistance	R_{sh}	1000 Ω
8	Series Resistance	R_s	0.0097 Ω
9	Irradiance Intensity	S_0	1000 W/m^2
10	Ambient Temperature	T	25 ºC

2.3. DC-DC buck converter

To implement the MPPT algorithm, a DC-DC Buck converter is used, which is installed between the PV array and the load. It is easy to control the load impedance and maintain the PV array at its GMPP condition by controlling the duty cycle switching converter. The parameters of DC-DC buck converter are obtained with the following model [24]:

$$V_o = D.V_{in} \tag{2}$$

$$D = \frac{T_{on}}{T_s} \tag{3}$$

$$L_{min} = \frac{(1-D)R}{2f} \tag{4}$$

$$L = \left(\frac{V_{in}-V_o}{\Delta i_L f}\right) D \tag{5}$$

$$C = \frac{1-D}{8L\left({}^{\Delta V_o}/{}_{V_o}\right)f^2} \tag{6}$$

where V_{in} is the input voltage, V_o is the output voltage, D is the duty cycle, T_{on} is the duration of the PWM signal to turn on the converter switch, T_s is the switching period, L_{min} is the minimum inductance required for the continuous current operation, R is the load resistor. L is the filter inductor and C is the filter capacitor. When, f is the switching frequency, ΔV_o is the output ripple voltage, and Δi_L is the inductor ripple current. The parameters of DC-DC buck converter as shown in Table 2. Then, the equivalent circuit of DC-DC buck converter as shown in Figure 3.

Table 2. The parameters of buck converter

No.	Parameter	Variable	Value
1	Switching Frequency	f	20 kHz
2	Inductor	L	1.11 mH
3	Capacitor	C	177.15 µF
4	Load Resistor	R	3.528 Ω

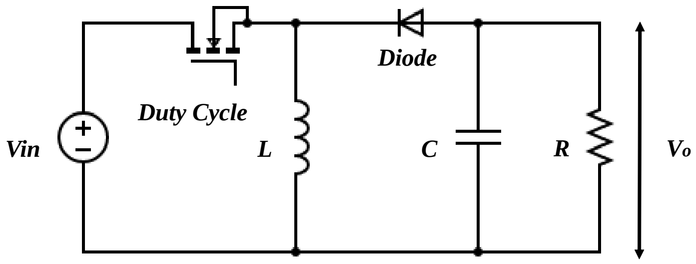


Figure 3. The equivalent circuit of DC-DC buck converter

2.4. TSA based MPPT (TSA-MPPT)

The TSA global optimization algorithm described in paper [20] is now applied as an MPPT technique for PV array systems operating under uniform irradiation and non-uniform irradiation through direct control. In TSA-MPPT, each tunicate search agent is defined as the duty cycle (D) of the DC-DC converter. In first iteration, the random duty cycle initialization at 5 point positions where the range of duty cycle are 0% until 100%. Then the position of each duty cycle called $D(i)$. If we use 5 positions of duty cycle as agents, the position can define as $[D_1, D_2, D_3, D_4, D_5]$. The position of each duty cycle will be evaluated by a fitness function. In this work, the fitness function utilizes the PV array output voltage (V_{pv}) and the PV array output current (I_{pv}). The best position is defined by how much PV array output power (P_{pv}) generated by the duty cycle. The fitness function in this work is formulated as (7).

$$P_{pv} = V_{pv} \times I_{pv} \tag{7}$$

Then, to update the duty cycle, the TSA algorithm depends on a random vector which is formulated as (8).

$$\vec{A} = \frac{c_2+c_3-(2 \cdot c_1)}{[P_{min}+c_1 \cdot P_{max}-P_{min}]} \tag{6}$$

Vector $\vec{A}$ is a random vector to avoid conflicts between agents. Where c_1, c_2, and c_3 are random numbers with range [0,1]. P_{min} and P_{max} are the initial and subordinate speeds with values are 1 and 4, respectively. Then, for the position of duty cycle to ensure around the MPP can be formulated in (9). So, for update the duty cycle can be formulated in (10):

$$D(i) = \begin{cases} D_{best} + \vec{A} \cdot |D_{best} - r_{and} \cdot D(i)| & \text{if } r_{and} \geq 0.5 \\ D_{best} - \vec{A} \cdot |D_{best} - r_{and} \cdot D(i)| & \text{if } r_{and} < 0.5 \end{cases} \tag{9}$$

$$D(i+1) = \frac{D(i)+D(i+1)}{2+c_1} \tag{10}$$

where $D(i+1)$ represents the updated duty cycle and r_{and} is random value with range [0,1]. The flowchart of TSA-MPPT as shown in Figure 4.

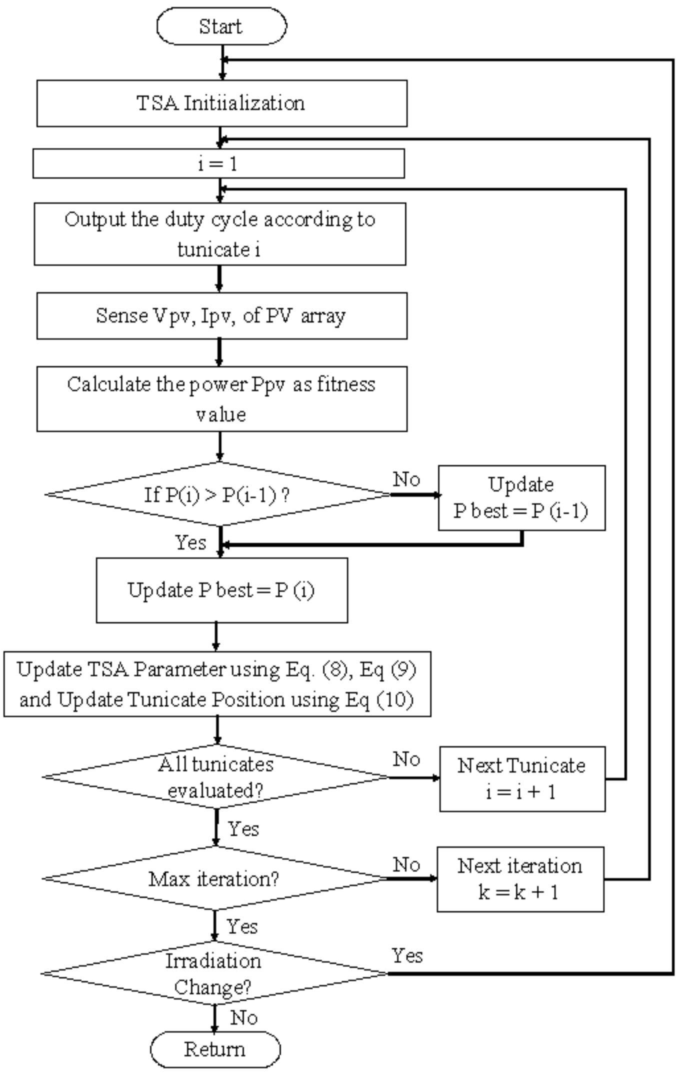


Figure 4. Flowchart of TSA-MPPT

The step by step for TSA-MPPT are:

- Step 1: Initialize the position of duty cycles $D(i)$ and TSA parameters such us $P_{min} = 1, P_{max} = 4$, $c_1, c_2, c_3, r_{and}, \vec{A}$, Max Iteration=10
- Step 2: Sense the PV array output voltage (V_{pv}) and the PV array output current (I_{pv}) generated by duty cycle $D(i)$.
- Step 3: Calculate the PV array output power (P_{pv}) generated by duty cycle $D(i)$ with (7).
- Step 4: Evaluate the position of duty cycle by how much the PV array output power (P_{pv}) generated by the position of duty cycle $D(i)$.
- Step 5: Update the TSA parameters using (8) and (9), then update the position of duty cycle with (10)
- Step 6: Increase iteration step by step, and if not the same to Max Iteration, repeat step 2 until step 5
- Step 7: Output the best position of duty cycle obtained so far for control switching of DC-DC buck converter. The best duty cycle position must be generated PV array output power (P_{pv}) at GMPP.

3. RESULTS AND DISCUSSION

For implementing the TSA-MPPT, it is validated using a simulation with PowerSim (PSIM) 9.1.1 software, as shown in Figure 5. PV array arranged by 5 PV modules connected in series integrated with DC-DC Buck converter. Furthermore, to determine the algorithm's performance, TSA-MPPT is compared with the P&O-MPPT [25], [26] and PSO-MPPT [10]. The system was tested under several conditions with uniform irradiation and non-uniform irradiation. Five cases are used to test and analyze the performance of each algorithm. In case 1, PV array in non-shading condition with uniform irradiation, which is the PV array characteristic have only one MPP. In case 2, case 3, case 4, and case 5, PV array under partial shading condition with different irradiation levels, which is the PV array characteristics have several MPP. The illustration of PV array characteristics in 5 cases is shown in Figure 6. From the figure, can know that each of cases have different characteristic with other. Besides that, TSA-MPPT also tested under fast varying irradiation change. The purpose of the TSA-MPPT is to reach the GMPP and maintain the duty cycle stay at GMPP.

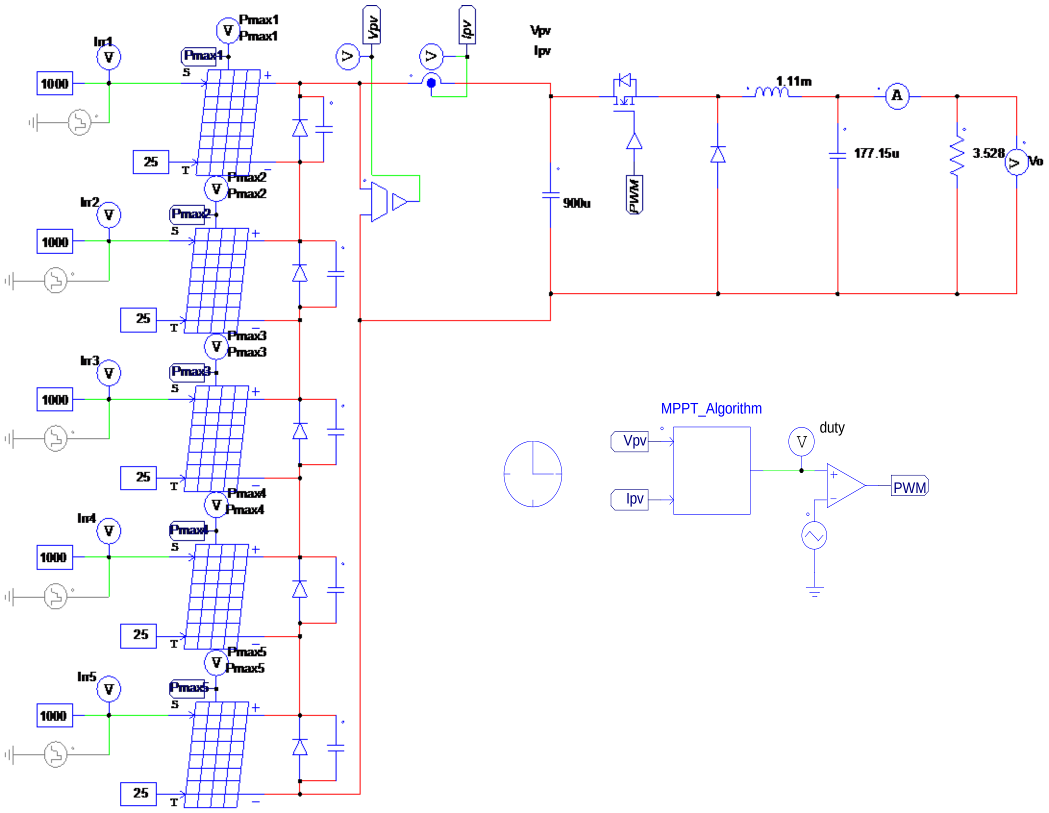


Figure 5. Simulation circuit in PSIM

3.1. Under uniform irradiation

In case 1, TSA-MPPT was tested under non-shading conditions with uniform irradiation of 1000 W/m^2 while the temperature was assumed to be constant at 25 ºC. The simulation results show power tracking to MPP and duty cycle movement is shown in Figure 6. For the P&O-MPPT, the change in duty cycle movement by a fixed step of 3%. As for the PSO-MPPT and TSA-MPPT, the duty cycle changes follow each algorithm's random variable step size. From the simulation results in Figure 7, the P&O-MPPT reaches the MPP point quickly at t=0.15 s, but there are oscillations in the MPP condition. Therefore, it cannot be stable for both the power and duty cycle.

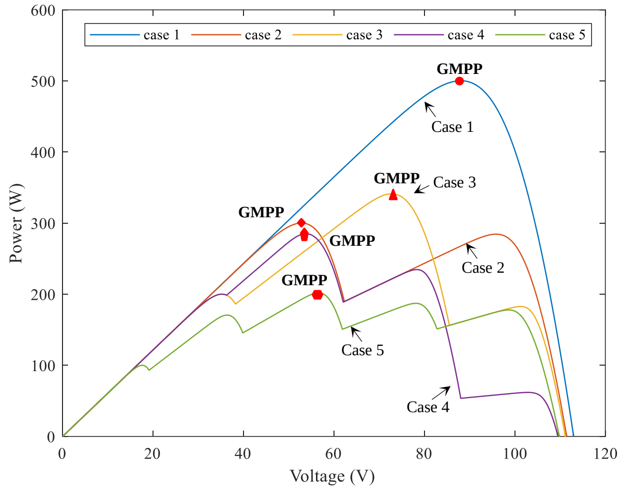


Figure 6. PV characteristic of five cases

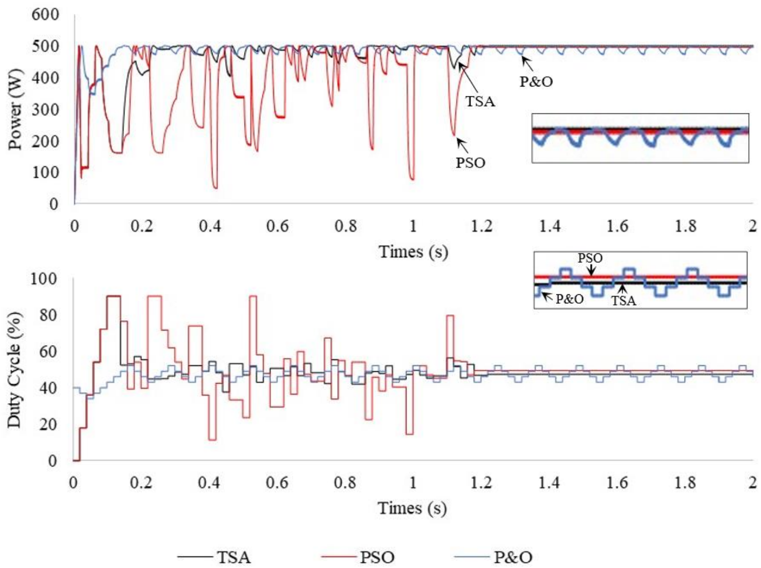


Figure 7. The simulation result of case 1: power and duty cycle waveform

On the other side, the PSO-MPPT can track GMPP correctly at t=1.2 s, and there is no oscillation during MPP conditions. Still, there is a very fluctuating power transient before reaching MPP. With TSA, it can track MPP correctly at t=1.2 s, there is no oscillation during MPP, and power fluctuations before reaching MPP are also more stable when compared to PSO-MPPT. With the TSA-MPPT, in this condition, it has an accuracy of 99.96%. From the comparison results, the performance of PSO and TSA has the same time convergence characteristics to reach the MPP point. However, TSA-MPPT is superior in reducing power fluctuations before reaching the MPP, and there is no oscillation after reaching the MPP.

3.2. Under non-uniform irradiation

To determine the algorithm's performance for tracking GMPP under non-uniform irradiation conditions, TSA-MPPT was tested in 4 cases of non-uniform irradiation with different partial shading levels, and the temperature was assumed to be constant at 25 °C. In case 2, the PV array is assumed to receive irradiation with two different irradiation levels, 1000 W/m^2, and 500 W/m^2. The PV array characteristic have 2 MPP points, as shown in Figure 6. TSA-MPPT and PSO-MPPT successfully tracked GMPP correctly, but P&O-MPPT cannot track the GMPP, so the power generated is below the actual GMPP power, as shown in Figure 8. TSA has the best performance for case 2.

In case 3, the PV array is assumed to receive irradiation with three different irradiation levels, 1000 W/m^2, 800 W/m^2, and 300 W/m^2. Therefore, the PV array characteristic have 3 MPP points, as shown in Figure 6. From the simulation results, TSA-MPPT, PSO-MPPT, and P&O-MPPT successfully tracked GMPP correctly. Still, for P&O-MPPT, there were power oscillations during MPP, as well as PSO-MPPT, there was a very fluctuating power transient before reaching MPP, as shown in Figure 9. Thus, TSA still has the best performance when compared to P&O-MPPT and PSO-MPPT for case 3.

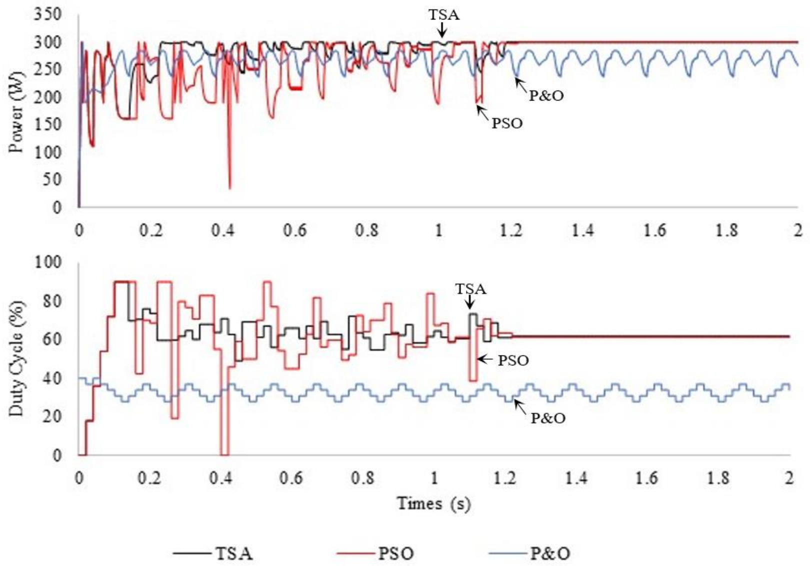


Figure 8. The simulation result of case 2: power and duty cycle waveform

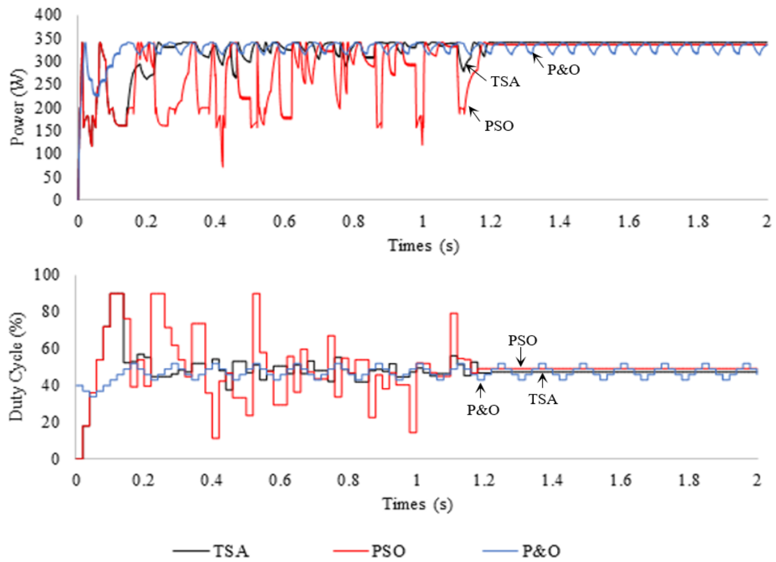


Figure 9. The simulation result of case 3: power and duty cycle waveform

In case 4, the PV array is assumed to receive irradiation with four different irradiation levels, 1000 W/m^2, 500 W/m^2, 900 W/m^2, and 100 W/m^2, so that the PV array characteristic have 4 MPP points, as shown in Figure 6. TSA-MPPT and PSO-MPPT managed to track GMPP correctly, but P&O-MPPT could not track GMPP, so the power generated was below the actual GMPP power, as shown in Figure 10. Thus, TSA has the best performance for case 4.

In case 5, the PV array is assumed to get irradiation with five different irradiation levels, namely 1000 W/m^2, 300 W/m^2, 400 W/m^2, 600 W/m^2, and 800 W/m^2. The the PV array characteristic have 5 MPP points, as shown in Figure 6. From the simulation results, TSA-MPPT, PSO-MPPT, and P&O-MPPT managed to track GMPP correctly. Still, for P&O-MPPT, there are power oscillations during MPP, as well as PSO-MPPT, there is a very fluctuating power transient before reaching MPP, as shown in Figure 11. Thus, TSA still has the best performance when compared to P&O-MPPT and PSO-MPPT for case 5. The detail of simulation results can be shown in Table 3.

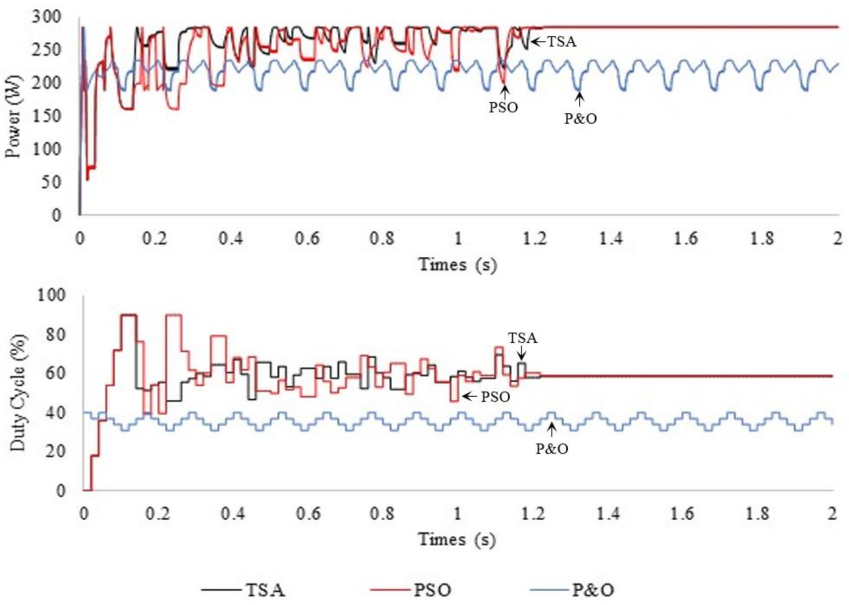


Figure 10. The simulation result of case 4: power and duty cycle waveform

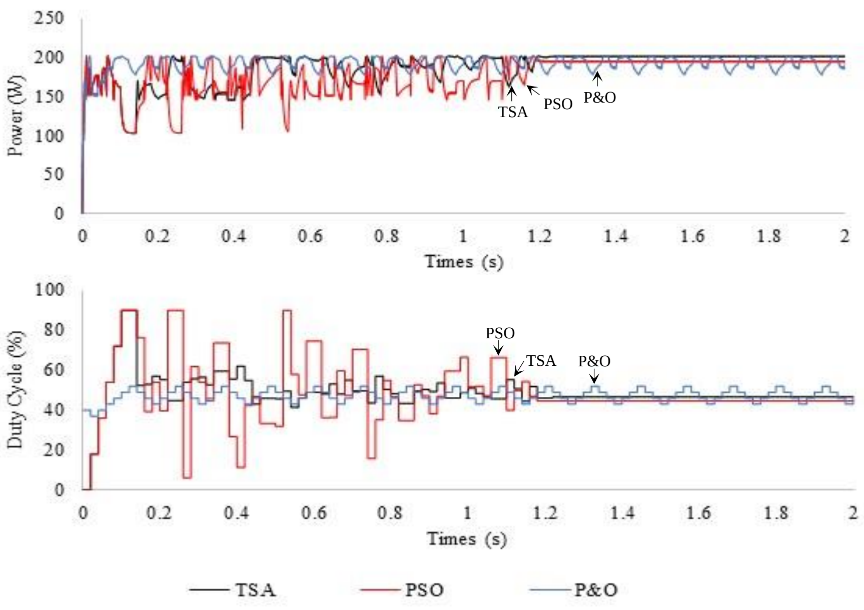


Figure 11. The simulation result of case 5: power and duty cycle waveform

3.3. Under varrying irradiation change

In addition, TSA-MPPT was also tested under varying irradiation change conditions [27]. First, the PV array is conditioned to receive uniform irradiation of 1000 W/m^2 for 1.6 s as 1st condition, then it changes to a non-uniform irradiation condition with 3 different irradiation levels, 1000 W/m^2, 500 W/m^2, and 100 W/m^2 for 1.6 s as 2nd condition, then the irradiation changed again with 5 different irradiation levels, 1000 W/m^2, 900 W/m^2, 700 W/m^2, 400 W/m$_2$, and 300 W/m^2 for 1.6 s as 3rd condition.

Table 3. Simulation results

Case	Method	Pmpp (W)	Pmppt (W)	Duty cycle (%)	Time to reach MPP (s)	Accuracy (%)
1	P&O	500.28	499.9	49	0.15	99.92%
	PSO		495.61	49.37	1.2	99.07%
	TSA		500.09	47.33	1.2	99.96%
2	P&O	300.1	284.34	31	0.12	94.75%
	PSO		300	61.4	1.22	99.97%
	TSA		300.06	61.8	1.2	99.99%
3	P&O	341.28	340.79	49	0.15	99.86%
	PSO		336.5	49.21	1.22	98.60%
	TSA		341.09	47.33	1.22	99.94%
4	P&O	285.1	234.61	37	0.15	82.29%
	PSO		284.99	58.69	1.23	99.96%
	TSA		285.03	61.8	1.22	99.98%
5	P&O	202.03	201.85	49	0.1	99.91%
	PSO		194.78	44.65	1.2	96.41%
	TSA		201.51	46.56	1.22	99.74%

From the simulation results shown in Figure 12, TSA-MPPT has the best tracking ability compared to P&O-MPPT and PSO-MPPT, where TSA-MPPT succeeded in tracking GMPP in 3 irradiation conditions changes were quite fast with the accuracy is 99.9%. Meanwhile, P&O-MPPT is less precise in tracking GMPP during the 2nd condition change, and PSO-MPPT is less accurate in tracking GMPP in the 3rd condition. Overall, the comparison of the performance evaluations of TSA-MPPT, P&O-MPPT, and PSO-MPPT can be shown in Table 4.

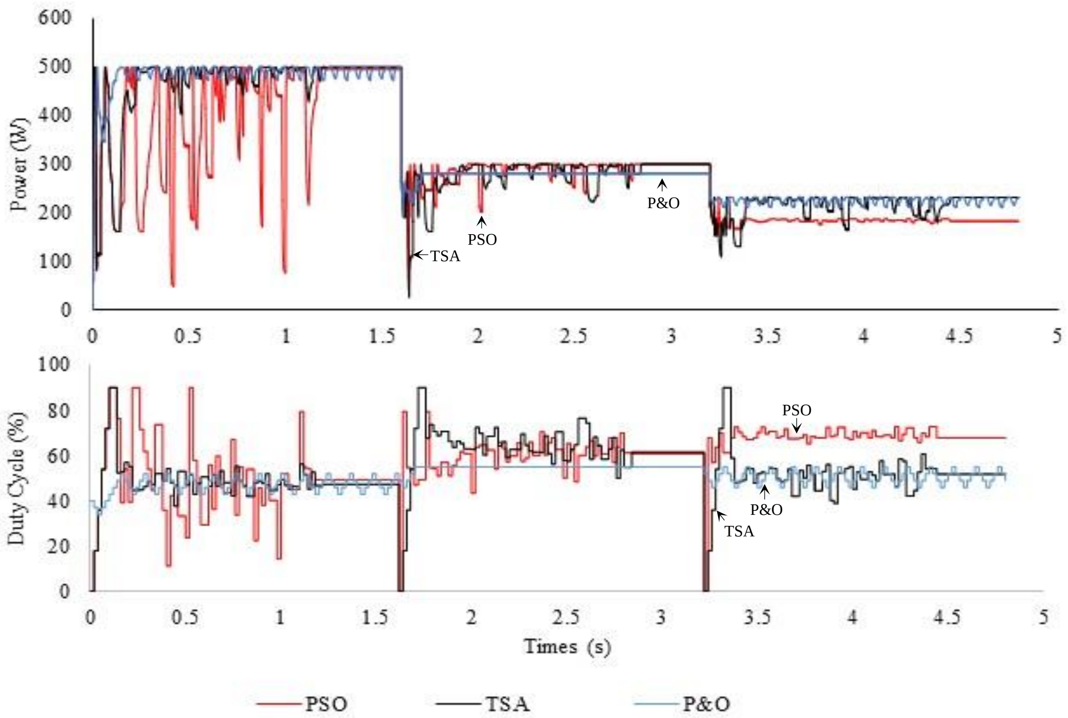


Figure 12. The simulation result of varrying irradiation change

Table 4. Performance evaluation

Method	Parameter	Performance Analysis
P&O	Duty cycle star=40% Duty cycle step=3%	- Faster tracking; - Has oscillation at MPP; - Good tracking for uniform irradiation - High accuracy.
PSO	Duty cycle initialization=5 {18%, 36%, 54%, 72%, 90%} MaxIteration=10 w_1=0.4 c_1=1.6 c_2=1.8	- Faster Tracking; - No oscillation at MPP; - Good tracking performance, but in several condition can't track GMPP - Have very fluctuating power and duty before reach MPP - High accuracy
TSA	Duty cycle initialization=5 {18%, 36%, 54%, 72%,90%} MaxIteration=10 P_{max}=4 P_{min}=1	- Faster Tracking; - No oscillation at MPP; - Good tracking performance for uniform and non-uniform irradiation condition; - Have fluctuating power and duty before reach MPP, but more stable than PSO; - High accuracy.

4. CONCLUSION

In this paper, the TSA-MPPT is proposed. TSA-MPPT have good performance both in tracking ability and accuracy. It has good tracking ability in both uniform and non-uniform irradiation conditions even for complex partial shading with five different irradiation levels. With almost zero steady-state oscillation at MPP. The accuracy of TSA-MPPT is 99,9%. The TSA-MPPT overall shows superior performance compared to the P&O-MPPT and PSO-MPPT. This paper is purposed to be a reference for researchers who developed MPPT algorithm based on bio-inspired metaheuristic algorithm for PV system. For the next study, we suggest improving the algorithm by tuning random variables or hybrid them with other algorithms to decrease the converge time.

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BIOGRAPHIES OF AUTHORS

Evi Nafiatus Sholikhah finished her bachelor and master degrees from the Department of Electrical Engineering at Politeknik Elektronika Negeri Surabaya (PENS) in 2020 and 2022, respectively. Her research interest includes power electronics and renewable energy. She can be contacted by email: evinafiatus30@gmail.com.

Novie Ayub Windarko finished his bachelor and master degree from Department of Electrical Engineering, Institut Teknologi Sepuluh Nopember Surabaya, Indonesia. He received his Ph.D from School of Electrical Engineering, Chungbuk National University, South Korea. He was a JICA junior visiting researcher in Hirofumi Akagi Lab., Tokyo Institute of Technology in 2002. He has been joining to PENS since 2000. He was the head of Renewable Energy Research Centre of PENS. He received the best paper and the best poster award at IEEE IES 2015. He has served as reviewers for IEEE Trans. on Transportation Electrification, IEEE Trans. on Power Electronics, Journal of Batteries, Journal of Energies and EMITTER International Journal of Engineering Technology. His research interests include power electronics converter, PV power generation and optimization for renewable energy. He can be contacted by email: ayub@pens.ac.id.

Bambang Sumantri is a lecturer of Politeknik Elektronika Negeri Surabaya (PENS), Indonesia. He received bachelor degree in Electrical Engineering from Institut Teknologi Sepuluh Nopember (ITS), Indonesia, in 2002, M.Sc. (Master of Science) in Control Engineering from Universiti Teknologi Petronas, Malaysia, in 2009, and Doctor of Engineering in Mechanical Engineering, Toyohashi University of Technology, Japan, in 2015. His research interest is in robust control system, embedded controller and renewable energy. He can be contacted by email: bambang@pens.ac.id.