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Particle Swarm Optimization (PSO) based Photovoltaic MPPT Algorithm under Partial Shading Condition

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Abstract

The efficiency of a solar photovoltaic (PV) system experiences a substantial decline when shadows obscure the PV array's surface, leading to a decrease in power production. In cases of partial shading, the PV array exhibits multiple peaks in its characteristic curve, causing inefficiencies in the traditional maximum power point tracking (MPPT) algorithm. In response to this challenge, we have proposed an optimization method for PV systems using the particle swarm optimization (PSO) algorithm in MPPT, aiming to enhance power extraction during shaded conditions. We assessed the performance of our MPPT methods by comparing tracking time, tracking error, and efficiency with perturb and observe (P&O) and incremental conductance (IC) algorithms. We generated random shading patterns through a partial shading generator function and conducted simulations of a PV system containing ten PV modules connected to a DC dummy load via a DC-DC boost converter using MATLAB/SIMULINK. Simulation results indicated that the PSO-based MPPT method effectively located global maximum power point (GMPP) while the P&O and IC MPPT methods remained confined to local maxima. Furthermore, the PSO optimization substantially improved the PV system's efficiency by approximately 4.66% under dynamic shading conditions, albeit with a slightly slower tracking time compared to the P&O and IC MPPT methods featuring delays of 0.0025 s and 0.0105 s, respectively.

Keywords: PSO, MPPT, MATLAB/SIMULINK.

I. INTRODUCTION

Renewable energy has gained widespread adoption across the globe as a vital source for generating electricity. Ongoing research endeavors are dedicated to advancing renewable energy technologies utilized in power plants, such as solar photovoltaic (PV), wind, offshore tidal wave and hydro. The key to the successful deployment of renewable energy lies in developing resilient technologies that offer efficient power generation at a cost-effective price. This is particularly important because the output of renewable energy sources depends significantly on unpredictable environmental conditions. Consequently, there exists substantial potential to expand the role of renewable energy in meeting global energy needs, surpassing fossil fuels, which have traditionally served as the dominant energy source. Solar energy, in particular, stands out as the most abundant renewable resource on Earth [1], presenting significant opportunities for harnessing this valuable energy source.

Solar energy is subject to weather conditions and can be adversely affected by factors like shading [2], leading to a significant reduction in the PV power output [3]. When part of a PV array is shaded, it results in multiple localized power points [5] due to the presence of bypass diodes. These diodes are designed to prevent overheating in shaded areas caused by reverse current, and this can lead to several peaks in the PV's power-voltage characteristic curve. Some traditional algorithms used in the maximum power point tracking (MPPT) methods, such as perturb and observe (P&O) and incremental conductance (IC), can only identify these local maxima. Consequently, failure to accurately track the true global maximum power point (GMPP) results in power losses and a subsequent reduction in the efficiency of the PV system [6-7].

Numerous solutions addressing the challenge of partial shading in PV systems have been extensively examined in existing literature. In their work, Ali Bidram [8] did a comprehensive overview of various techniques, encompassing MPPT control, array configurations, system architectures, and converter circuit topologies. However, the utilization of MPPT systems is still the most cost-effective approach for enhancing the overall efficiency of PV affected by shading [9]. Furthermore, modifications to conventional MPPT algorithms, such as modified IC, have been suggested in previous research [10-11] and subsequently validated through experimental setups. In low irradiance level scenarios, research conducted by Yongheng Yang and Frede Blaabjerg [12] has shown that modified P&O algorithm, incorporating a deadbeat control approach, results in improved tracking response and reduced steady-state oscillations. Nevertheless, when dealing with rapidly changing environmental conditions, whether it's variations in insolation levels or shading patterns, soft computing methods such as fuzzy logic, artificial neural networks, and evolutionary algorithms (EA) are better suited and exhibit promising results than conventional MPPT techniques [9, 13].

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A noteworthy EA technique that attracts significant attention among researchers is the implementation of the particle swarm optimization (PSO) algorithm within MPPT systems, which is employed to address the limitations of conventional MPPT methods in accurately tracking the true GMPP during shading events [7, 14-16]. The PSO, which is rooted in the optimization of particle movements, proves effective in identifying the maximum power point (MPP) in diverse and unique shapes of the Photovoltaic (PV) power-voltage (P-V) characteristic curve resulting from dynamic environmental conditions, including partial shading events [17]. In this paper, the PSO algorithm is proposed in the MPPT system to optimize the PV system, particularly under partial shading conditions. Simulations were conducted using MATLAB/SIMULINK, where the results were compared against those obtained from the two traditional MPPT algorithms, P&O and IC. The remainder of this paper is organized as follows. In the next section, we will present the modeling of the PV system, offering a brief explanation of the PV system model and the techniques for modeling partial shading conditions based on prior research [18]. Furthermore, we describe the partial shading generator model and present a case study of partial shading conditions. The methodology, encompassing the MPPT algorithms, is reviewed briefly within this paper with discussions on various aspects, including performance analysis. Finally, we delve into the simulation results of the proposed PSO-based MPPT approach and compare the outcomes of the two conventional algorithms. In the last section, we draw our conclusions.

II. Materials and Methods

A. PV Modeling

An independent photovoltaic (PV) system, often referred to as a stand-alone PV plant, operates independently from the electrical grid. This category of solar power generation can be categorized into three distinct types: direct-coupled system, stand-alone PV system with storage, and hybrid stand-alone PV system. The simplest among these is the direct-coupled PV system, which includes a PV array, a DC-DC converter, and a DC load [19]. Figure 1 illustrates a schematic diagram of the direct-coupled configuration in a stand-alone PV system.

Generation of the desired power in a photovoltaic (PV) array involves connecting several PV modules in a combination of series and parallel connections. The amount of power generated depends on the level of irradiance received by each PV module [10, 20]. A PV module is composed of multiple PV cells interconnected in both series and parallel configurations. Serial connections increase the voltage output, while parallel connections increase the current [21]. Figure 2 presents an equivalent circuit model of the PV cells with a single diode. Equation 1 below represents the PV cell current model [25]:

$$I_{pv} = I_g - I_s\left(exp\left(\frac{q(V_{pv}+I_{pv}\cdot R_s)}{nkT}\right) - 1\right) \quad (1)$$

where I_{pv} is the PV's output current, I_g is the current source, I_s is the saturated current of the diode, q is the electron charge (1.60217646 x 10^{-19} C), n is the ideality factor of diode, k is Boltzmann's constant (1.3806503 x 10^{-23} J/K), T is the temperature in Kelvin, R_s is the equivalent series resistance and V_{pv} is the output voltage of the PV.

Figure 3 illustrates a schematic representation of a boost-type DC-DC converter as an interface between the PV array and the load in the direct-coupled PV system. The boost converter relies on the duty cycle provided by the MPPT controller, while the algorithm implemented in the MPPT controller is responsible for conducting the tracking process to identify the MPP [18].

The duty cycle expressed in Equation 2 below is a function of the input voltage and the converter output voltage [22]:

$$V_o = \frac{V_{in}}{1-D} \quad (2)$$

where V_o is the output voltage, V_i is the input voltage, and D is the duty cycle of the converter. In order to step up the output voltage, the value of D must be less than 1.

B. Partial Shading Condition Model

The modeling of the shaded condition in a PV module is derived from the study conducted by Patel et al. [18]. The shaded portion of a PV module is a representation of a collection of PV cells that receive less solar insolation compared to other groups of PV cells.

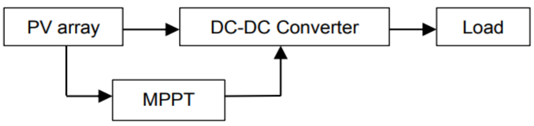


Figure 1. Diagram of direct-coupled stand-alone PV.

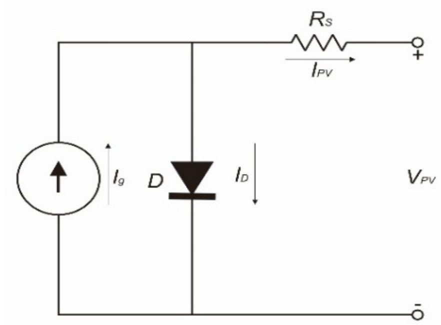


Figure 2. Equivalent circuit of PV cell [21].

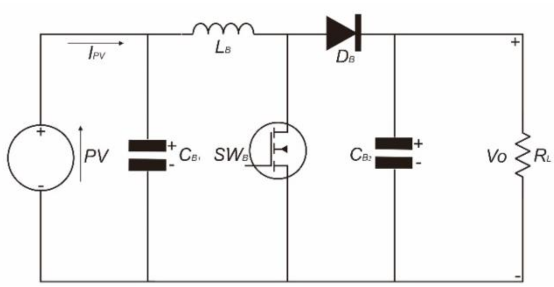


Figure 3. Schematic diagram of boost converter [18].

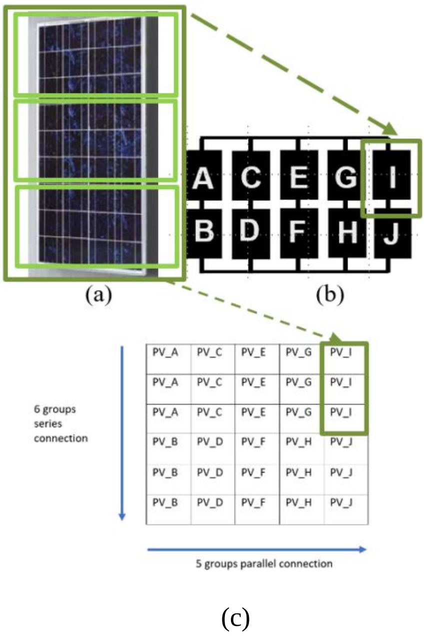


Figure 4. PV module viewed as groups of PV cells.

The manner in which PV cells are grouped for modeling is directly influenced by the number of PV cells within a module. As a result, the modeling of partial shading conditions in a PV array, which includes several PV modules, can be achieved by organizing PV cells and distinguishing the insolation levels among these groups of PV cells.

Figure 4 illustrates the arrangement of PV cells within a PV module. In Figure 4a, a PV module named the Mitsubishi PV-EE130MF5F contains 36 PV cells, while Figure 4b displays a PV array composed of 10 PV modules labeled with alphabet letters. These modules are interconnected in a configuration with 2 in series and 5 in parallel. Moreover, in Figure 4c, there are 30 groups of PV cells indicated by green lines. These 30 PV cell groups are derived from the ten PV modules, with each PV module's cells organized into three separate groups, as shown by green lines in Figure 4a.

To describe condition of partial shading in the PV array, a partial shading generator is employed. Shading patterns can be created randomly by taking into account the number of PV cell groups and their specific configurations. An example of pseudo-MATLAB code is illustrated in Algorithm 1 and is utilized for this purpose.

This paper discusses three different case studies, which are uniform insolation condition, static partial shading condition, and dynamic partial shading condition. In the uniform scenario, all PV cells receive the same level of insolation. On the other hand, the shaded conditions are categorized into two types based on time. Static partial shading refers to a condition where the shading pattern applied to the PV array remains constant over time. Dynamic partial shading, on the other hand, involves variations in the shading pattern over time, thus making it time-variant.

C. MPPT Algorithms

The optimization of a PV system through maximum power point tracking (MPPT) can be achieved by conducting a comparative analysis of the proposed MPPT method as in reference [23]. In this paper, the comparative analysis was carried out using three distinct MPPT algorithms, specifically P&O, IC, and PSO.

1) Perturb and Observe (P&O)

The two most commonly used MPPT algorithms excel primarily in uniform insolation conditions. The P&O algorithm operates by perturbing the voltage and then measuring the change in power with respect to the voltage alteration [6]. When the measured power exhibits no change, the peak power point is reached. The direction of the next perturbation is determined based on the voltage and power difference with respect to zero. A pseudo-code representation of the P&O-based MPPT algorithm is presented in Algorithm 2.

2) Incremental Conductance (IC)

The incremental conductance (IC) algorithm shares a similar concept with the P&O algorithm when it comes to the MPP. When the derivative of power with respect to voltage reaches zero, the maximum power point is reached. Equation 3 in the paper outlines the implementation of the IC algorithm, which determines the direction of tracking movement [6]. The IC algorithm takes voltage and current as inputs with the duty cycle being configured. IC is represented as (ΔI/ΔV), and when the increment is equal to the conductance (-I/V), the MPP is achieved, hence requiring no further movement. The tracking shifts from left to right when the increment is lower than the conductance, indicating that the MPP is located to the right and vice versa. Algorithm 3 provides a pseudo-code representation of the IC MPPT algorithm.

Algorithm 1: Random Pattern Generator

```
Function RandPattern (G_i,n_s,n_p,n_e);
Input: G_i ← insolation level vector;
n_s ← number of series-connected cells;
n_p ← number of parallel-connected cells;
n_e ← number of shading event changes;
Output: P_i ← Shading Patterns
For i=1:n_e do
        Rng(i) ← assign random seed number
        P_i(i)=rand(G_i,[n_s n_p])
end
```

Algorithm 2: Perturb and Observe

```
Function PO (V_pv,I_pv,Δd);
Input: V_pv ← photovoltaic voltage;
I_pv ← photovoltaic current;
Δd ← perturbation magnitude;
Output: d ← duty cycle
While t<t_stop do
        If Δd>0
            If P_t>P_t-1
                        d=d+Δd; ← move to the right
            Else
                        d=d-Δd; ← move to the left
            end
        Else
            If P_t>P_t-1
                        d=d-Δd; ← move to the left
            Else
                        d=d+Δd; ← move to the right
            end
        end
end
```

$$\begin{cases} \frac{\Delta P}{\Delta V} = 0 & optimum \\ \frac{\Delta P}{\Delta V} > 0 & move\ right \\ \frac{\Delta P}{\Delta V} < 0 & move\ left \end{cases} \quad (3)$$

3) Particle Swarm Optimization

The most widely recognized evolutionary algorithm is the particle swarm optimization (PSO) algorithm. Its capability to track and discover optimal solutions relies on the performance of the best particle. In this algorithm, each particle represents a potential solution candidate, and the position of each particle is continuously updated, as demonstrated in Equation 4 [9].

$$x_i^{k+1} = x_i^k + \Phi_i^{k+1} \quad (4)$$

The updated position of a particle denoted by x_i^{k+1} is determined by the summation of its previous position x_i^k , and particle's velocity, i.e. Φ_i^{k+1}. The speed of a particle is determined using several parameters including the inertia weight, uniformly distributed random numbers, acceleration coefficients, the best position of the individual particle and the best position global particle indicated by $w, r_1, r_2, c_1, c_2, P_{best}$ and G_{best}. Equation 5 provides formula for calculating the velocity of a particle [9]. The PSO based MPPT code is presented in Algorithm 4.

$$\Phi_i^{k+1} = w\Phi_i^k + c_1 r_1\{P_{\text{best}i} - x_i^k\} + c_2 r_2\{G_{best} - x_i^k\} \quad (5)$$

D. Performance Analysis

The comparative analysis of MPPT performance involves the observation of three parameters to assess tracking time, tracking error, and efficiency derived from the simulation. The tracking time reflects the convergence time required for the algorithms to reach the GMPP. It examines how quickly the algorithms respond to dynamic changes in the environmental conditions. The second parameter, tracking error, measures the discrepancy between the obtained MPP determined by the algorithms and the true global MPP. It quantifies the accuracy of the algorithms in finding the MPP. The third parameter assesses the efficiency of the PV array calculated using the mean squared error (MSE). The MSE helps determine the difference between the MPP and the tracked power resulting from the application of the algorithm by providing insights into the overall performance. Equation 6 outlines the formula for calculating the MSE:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2 \quad (6)$$

where $(\frac{1}{n}\sum_{i=1}^{n})$ is the mean, while $\left(Y_i - \hat{Y}_i\right)^2$ is the squares of the errors.

III. Results and Discussion

A. System Implementation

A PV system model has been created in SIMULINK. The PV array is designed to have a power capacity of 1.3 kWp, which is achieved by combining 5 strings. Each string consists of 2 series-connected PV modules, each with a capacity of 130 Wp. The specific PV module used in the simulation of the PV array is the Mitsubishi PV module type PV-EE130MF5F. Additionally, the component values for the boost converter, which includes capacitors and inductors, are provided in Table 1.

Figure 5 illustrates the schematic of the PV system developed within SIMULINK. A DC-DC boost converter serves as an interface between the PV array and a DC dummy load. Furthermore, the boost converter is employed by the MPPT system, which functions in a

TABLE 1
BOOST CONVERTER COMPONENTS

Components	Value
C_1	500 μF
C_2	60 μF
L	2.6 μH

Algorithm 3: Incremental Conductance

```
Function IC (Vpv,Ipv,Δd);
Input: Vpv ← photovoltaic voltage; Ipv ← photovoltaic current; Δd ← perturbation magnitude;
Output: d ← duty cycle
While t<tstop do
    If Pt-Pt-1=0
        d=d; ← at MPP
    Else
        If Pt>Pt-1
            If Vt>Vt-1
                d=d+Δd; ← move to the right
            Else
                d=d-Δd; ← move to the left
            End
        Else
            If Vt>Vt-1
                d=d+Δd; ← move to the right
            Else
                d=d-Δd; ← move to the left
            End
        end
    end
End
```

Algorithm 4: Particle Swarm Optimisation

```
Function PSO (Vpv,Ipv,np,w,c1,c2);
Input: Vpv ← photovoltaic voltage; Ipv ← photovoltaic current; np ← number of particles;
w ← inertial weight;  c1 ← individual constant;  c2 ← social constant;
Output: d ← duty cycle
% initialise variables
X ← Initial particles; B ← Initial best particles; V ← Initial velocities; F ← Initial fitness value;
G ← Initial global best particle;
While t<tstop do
    For i=1:np
        F(Xi) ← Compute new fitness;
        If Fi,k-1<Fi,k
            Bi=Xi ← Update best individual particle
        End
    End
    % sort best individual particle and choose the best one
    Sort(Bk);
    % update global best particle
    G=B1;
    End
    % compute the velocity update
    Vk=(w·Vk-1)+c1·rand·(Bk - Xk-1)+c2·rand·(G - Xk-1);
    % compute the position update
    Xk=Xk-1+Vk;
End
```

centralized manner to determine the operating point for both current and voltage, thus facilitating the acquisition of the true GMPP. Within this setup, three distinct MPPT algorithm blocks are incorporated into different sections, and the simulation of each MPPT method is performed alternately. The output of the MPPT block is the duty cycle, which is then utilized to control the switching device of the boost converter.

The selection of a boost converter is motivated by the PV system's need for a higher voltage output, which necessitates voltage stepping up. Additionally, the choice of a boost converter is influenced by its reputation as one of the simplest and most easily controllable types of DC-DC converters, as indicated in reference [24].

B. Simulation Results

Simulation of the 1.3 kW-rated PV system incorporating the MPPT methods has been conducted in SIMULINK. The P&O and IC MPPT methods were implemented using SIMULINK blocks, while the proposed PSO MPPT was developed using MATLAB m-file code scripts. Parameters for the PSO MPPT determined from default values of the MATLAB toolbox can be seen in Table 2. Swarm size is limited to 4 particles as to target cheap computation. Thus, tracking delay could be minimized. MPPT performance is assessed in three different simulations of shading scenarios.

1) *Uniform Condition*

In this scenario, the PV array experiences uniform insolation across the entire surface of the PV module. The simulation results of the P&O, IC, and PSO MPPT algorithms are depicted in Figure 6 under an insolation level of 1000 W/m2. The IC algorithm extracts approximately 1300 Watts of power, whereas both the

TABLE 2
PSO PARAMETERS

Parameters	**Value**
Number of particles	4
Inertial Weight (w)	0.1-1.1
Individual cognitive constant (c_1)	1.49
Social cognitive constant (c_2)	1.49

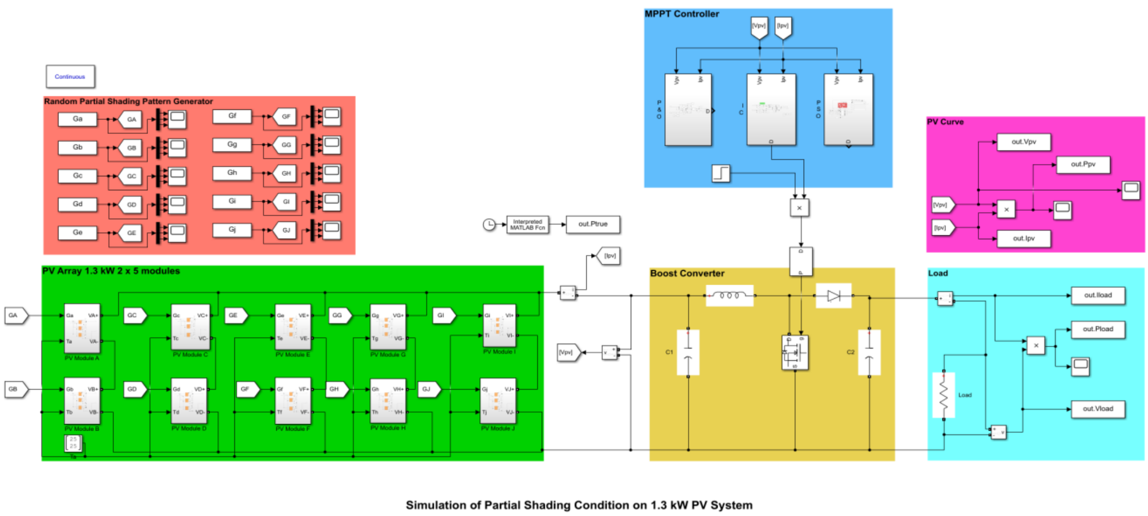


Figure 5. Diagram of 1.3 kW PV system built in SIMULINK.

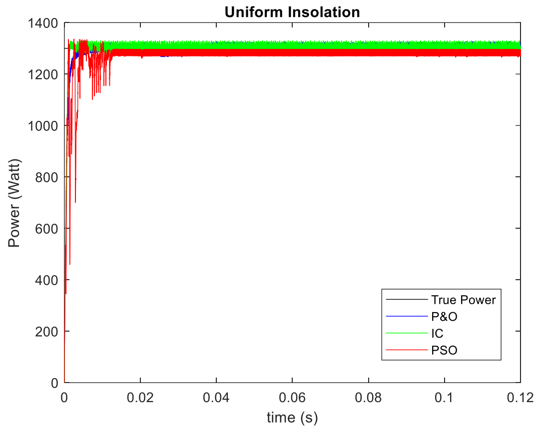


Figure 6. Power generated by the PV array at uniform insolation

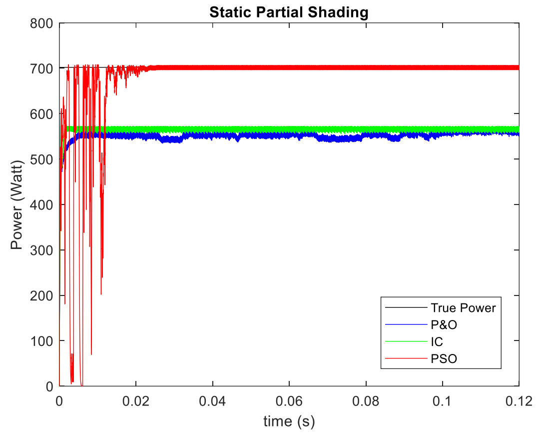


Figure 8. Power curve of the PV array at static partial shading condition

PSO and the P&O algorithms achieve 1290 Watts, which is slightly lower than the power obtained by the IC algorithm.

2) Static Partial Shading

The simulation of a static partial shading scenario is implemented to assess MPPT performance at the early stage of algorithm investigation. In this simulation scenario, the power-voltage characteristic curve is depicted in Figure 7. The curves representing the power generated by the PV array using the three MPPT algorithms are shown in Figure 8. In Figure 7, the results reveal the presence of three local maxima. The true GMPP is situated at an operating point with a voltage of 36.25 Volts and a power output of 702.5 Watts. The proposed PSO MPPT demonstrates its success in tracking the GMPP, while the other two algorithms can only identify local maxima located at an operating point with a voltage of 24.25 Volts and a power output of around 550 Watts.

3) Dynamic Partial Shading

To gain a more comprehensive understanding of MPPT operation, a dynamic partial shading scenario was introduced. The shading pattern changes at a rate of approximately 25 milliseconds. Although this rate is considered faster than the actual conditions in the real environments, it was chosen to accommodate the limitations of the computer hardware used in this project. The simulation was designed to effectively evaluate the

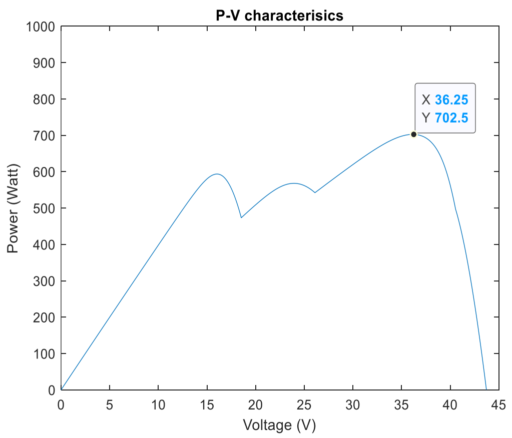


Figure 7. Power-voltage characteristic curve during static partial shading condition.

MPPT algorithms while taking these limitations into account. Table 3 presents the change of shading patterns, which consist of three different shading scenarios. The shading pattern commences and concludes with a uniform condition simulated at a full insolation level of 1000 W/m2.

The simulation results are presented in Figure 9. At each stage of the shading pattern implemented in the simulation, the proposed PSO MPPT exhibits outstanding tracking performance, as indicated by the red curve. In comparison, the P&O and IC MPPT algorithms are represented by the blue and green curves, respectively. The shaded conditions begin at times 0.02 seconds, 0.045 seconds and 0.07 seconds sequentially. The true power generated by the PV array during each shading pattern in dynamic partial shading conditions is recorded at 702.5 Watts, 730 Watts and 749 Watts, as shown by the black curve.

C. Discussion

Assessment of the MPPT algorithms is conducted by comparing the three parameters yielded by each MPPT algorithm. The first parameter is tracking time, which is evaluated from the results shown in Figure 6. It represents the power generated by the PV array during a scenario of uniform insolation at 1000 W/m2. In this context, the IC MPPT algorithm reaches the maximum power point at 0.002 seconds, making it the fastest algorithm compared to the P&O which requires 0.01 seconds to track the maximum power point. Meanwhile, the proposed PSO MPPT requires 0.0125 seconds, which is 2.5 milliseconds slower than the P&O algorithm and 10.5 milliseconds slower than the IC algorithm. The relatively slower tracking time of the proposed PSO is attributed to the computational complexity inherent in the PSO algorithm, which is greater than that of the P&O and IC algorithms.

The second parameter is tracking error, which was assessed in the simulation of a static partial shading condition, as shown in Figure 7. In this static partial shading scenario with the true GMPP located at an operating voltage of 36.25 Volts and a power of 702.5 Watts. The tracking abilities of each MPPT algorithm were as follows: 78.21% for the P&O, 80.13% for the IC and 96.96% for the proposed PSO MPPT. Consequently,

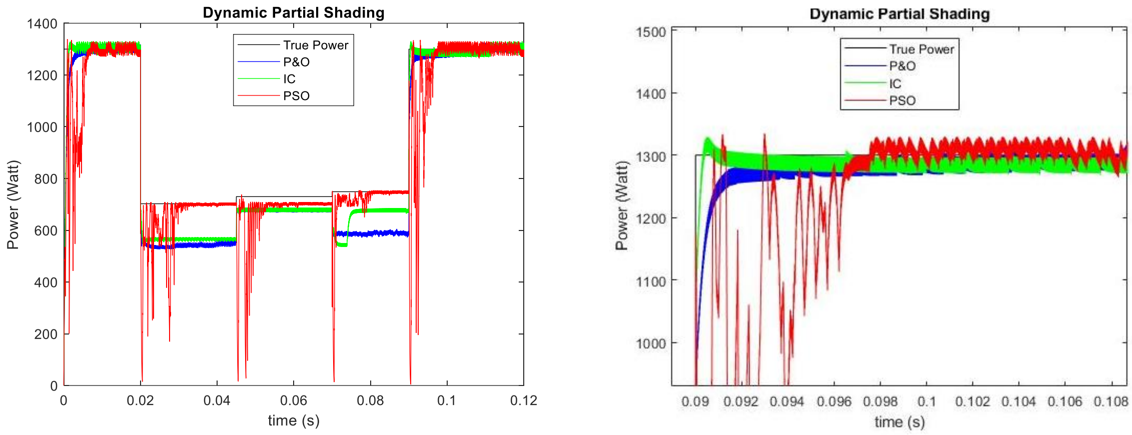
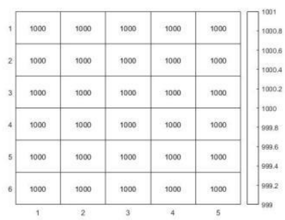
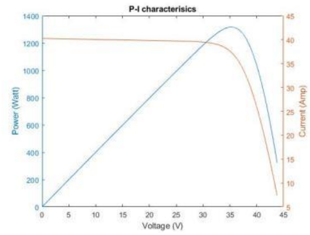
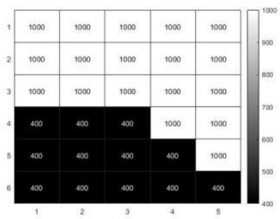
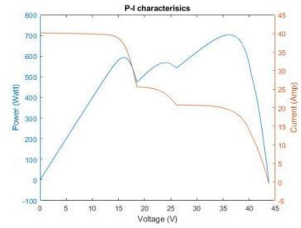
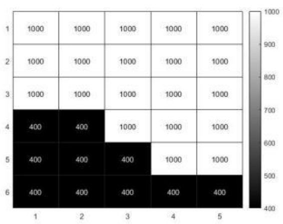
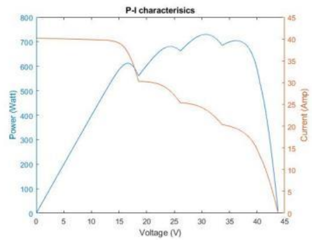
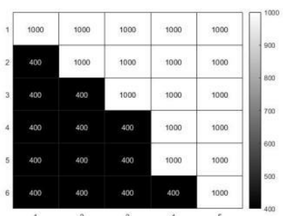
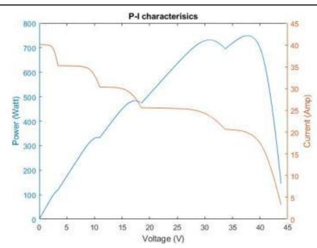


Figure 9. Power curve of the PV array at dynamic partial shading condition.

TABLE 3
SHADING PATTERNS DURING DYNAMIC PARTIAL SHADING CONDITION

Shading vents	Shading patterns	P-I characteristic curves
t=0s		
t=0.02s		
t=0.045s		
t=0.07s		

the tracking errors for these algorithms were approximately 21.79%, 19.87%, and 3.04%, respectively. The proposed PSO demonstrates the highest accuracy in tracking the true GMPP during partial shading conditions when compared to the other two algorithms. This means that the proposed PSO algorithm exhibits the smallest tracking error and is the most effective at finding the true GMPP under these conditions.

The results from the simulation of dynamic partial shading conditions are utilized to evaluate the third parameter, which is the efficiency of the PV system. In this partial shading scenario, the efficiency of the PV system utilizing the proposed PSO MPPT is enhanced by 4.66% compared to the PV system employing the P&O algorithm. Additionally, an approximate 1.8% efficiency improvement can be achieved by the proposed PSO MPPT compared to the IC algorithm. Consequently, optimizing the efficiency of the PV system is feasible when the tracking of the true GMPP is executed optimally.

IV. CONCLUSION

The PSO-based MPPT algorithm was introduced to enhance the optimization of the PV system to accurately track the GMPP, especially in partially shaded conditions. The simulation conducted in MATLAB/SIMULINK demonstrated that the proposed MPPT system effectively identifies the GMPP under both static and dynamic shading conditions. A comparative analysis of the simulation results revealed that the PSO MPPT algorithm can improve the efficiency of the PV system by 4.66% and 1.8% at an extra cost of the tracking time by 0.0025 seconds and 0.0105 seconds compared to the P&O MPPT algorithm and the IC MPPT algorithm respectively. This indicates that the proposed PSO MPPT algorithm significantly enhances the efficiency of the PV system with affordable delays in tracking time.

DECLARATIONS

Conflict of Interest

The authors state that there are no conflict of interests exist.

CRediT Authorship Contribution

Ersalina Werda Mukti is the main contributor of this paper. Ersalina Werda Mukti: Conceptualization, Methodology, Software implementation, Writing – Original Draft and Review; Agus Risdiyanto, Ant. Ardath Kristi and Rudi Darussalam: Writing - Review and Editing.

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