# Advanced particle swarm optimization for efficient and fast global maximum power point tracking under partial shading conditions

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**ABSTRACT**

Partial shading (PS) is a common issue in photovoltaic systems (PVs), and it can significantly reduce the system's output power. This paper presents the advanced particle swarm optimization (APSO) algorithm. APSO is designed to alleviate the challenges posed by PS in PVs in from where of effectiveness and stability speed so that it works to achieve and maintain the global maximum power point (GMPP) under PS conditions. It leverages persistent variables to store and track system states and iterations; it also includes checks to ensure that the duty cycle remains within specified bounds facilitating more effective optimization. Additionally, APSO optimizes solar panel duty cycles and velocities to converge toward an optimal solution to improve overall power generation efficiency and settling time. The results evaluation involves testing the performance of photovoltaic panels under three different shading scenarios and comparative analysis against recent Heuristic-optimization-based GMPP techniques, this study and comparative analyses demonstrate APSO's effectiveness and superiority in terms of high efficiency that reaches 99.85% and fast settling time of GMPP at less than 0.01 second across all test cases. APSO presents a promising solution for maximizing PV power output in the presence of partial shading.



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## 1. INTRODUCTION

The increasing adoption of photovoltaic (PV) technology within the worldwide energy sector marks a significant transition towards cleaner and more sustainable methods of power production. This notable surge resembles a global rebirth in how energy is generated, underscoring a pivotal moment in the history of energy. Scholars and researchers, as referenced in [1], [2], have extensively documented this remarkable expansion, highlighting the potential of renewable energy sources to address the environmental issues associated with traditional forms of energy generation. This transformation represents not only a shift in technological preferences but also a fundamental reevaluation of our relationship with the environment and our energy needs. As society increasingly recognizes the imperative to reduce carbon emissions and combat climate change, the widespread adoption of PV technology symbolizes a crucial step towards a greener and more sustainable future. This growing adoption of PV technology has spurred researchers' eagerness to develop and improve this clean energy source to make it more effective in power generation. Yet, as PV technology advances, it is confronted by a set of multifaceted challenges that demand innovative solutions. One of the fundamental challenges is the variability of environmental conditions, encompassing changes in temperature and solar irradiance, which directly impact the efficiency of a PV system. To harness the maximum available power, advanced techniques such as maximum power point tracking (MPPT) have become essential, as elucidated by [3]. This technology serves as the guiding compass, steering PVs toward the elusive maximum power points (MPPs) under dynamic environmental conditions.

Partial shading is an ever-present and intricate challenge in PVs. Shading can manifest in various forms, from the dappling of leaves to the transient cover of clouds, imposing temporary shadows upon PV panels. The consequence of PS is twofold: shaded sections of the PV string act as energy-absorbing loads, disrupting the harmonious flow of power, and the uneven distribution of solar irradiance spawn's hot spots, leading to a reduction in the overall system efficiency [4]. To address these issues, solutions such as bypass diodes, as advocated by study [5], have been introduced to reroute surplus current, thereby preventing the formation of hotspots. However, partial shading conditions (PSCs) introduce a new layer of complexity. The power-voltage (P-V) curve of PVs under PSCs exhibits multiple peaks, including both local maximum power points (LMPPs) and the single global maximum power point (GMPP). In response to these challenges, various MPPT algorithms have emerged classified into several groups: Traditional algorithms, meta-heuristic algorithms, hybrid algorithms, mathematics-based algorithms, artificial intelligence (AI) algorithms, algorithms exploiting characteristic curves, and miscellaneous algorithms [6], [7]. For instance, traditional and artificial intelligence MPPT algorithms like perturbation and observation (P&O) [8], hill climbing (HC) [9], incremental conductance (InC) [10], Fuzzy logic control (FLC) [11], and artificial neural network (ANN) [12]. Excel in uniform irradiation conditions due to their adept local search capabilities. However, when confronted with the intricacies of partial shading, their effectiveness diminishes, often settling for LMPPs instead of the desired GMPP, a result of their limited global optimization capabilities.

For this reason, the past decade has witnessed a surge in heuristic optimization algorithms, inspired by biological phenomena and physical principles, which have emerged as formidable tools to address the global maximum power point tracking (GMPPT) challenge. These algorithms including particle swarm optimization (PSO) [13], genetic algorithms (GA) [14], grey wolf optimization (GWO) [15], ant colony optimization (ACO) [16], gravitational search algorithm (GSA) [17], and cuckoo search (CS) [18]. Have demonstrated a remarkable ability to navigate the complexities of PSCs, converging efficiently on the GMPP, as affirmed by [19] these heuristic approaches represent a pivotal step toward enhancing MPPT efficiency. Despite their efficacy, heuristic optimization methods have limits in terms of seamlessly combining rapid settling time, achieving high efficiency, and ensuring a stable GMPP during continuous operation.

In this dynamic context, the paper introduces the APSO Algorithm, designed to optimize the performance of PV systems by ensuring efficient and fast GMPPT under PSCs. Tailored to tackle the intricate challenges posed by PSCs in PVs, APSO incorporates adaptive variables and sophisticated checks. These elements enable real-time optimization and adaptation of the duty cycle in a boost converter. The primary objective is to achieve and maintain the GMPP with high efficiency and rapid settling time. This approach significantly enhances the overall efficiency of power generation in PVs. The paper content is structured into five distinct sections: i) in section 2, we delve into the electrical modeling and characteristics of PVs under PSCs; ii) section 3 provides an extensive elaboration on the proposed algorithm; iii) section 4 is dedicated to the simulation outcomes, analysis, and a comparative study of the acquired results from the suggested technique with the five most recent meta-heuristic techniques; and iv) lastly, the concluding section encapsulates the final deductions drawn from the entire study.

## 2. ELECTRICAL CHARACTERISTICS OF THE PHOTOVOLTAICS UNDER PARTIAL SHADING CONDITIONS

### 2.1. The effect of partial shading conditions

Under PSCs, the electrical characteristics of PV strings undergo significant changes compared to uniform illumination. The most prominent effect is the emergence of multiple LMPPs instead of a single GMPP within the current-voltage (I-V) curve and power-voltage (P-V) curve as shown in Figure 1. Each illuminated section of a partially shaded PV string has distinct MPPs, leading to an uneven distribution of power production across the modules. This phenomenon often results in power losses due to the presence of shaded modules operating away from their respective MPPs. So, understanding the intricate electrical behavior of PV strings under PSCs is crucial in optimizing solar photovoltaic systems. The I-V and P-V relations of a PV module expanded to encompass bypass diodes are articulated by (1) [20]. At the same temperature, PV modules exposed to low sun irradiation will produce less current than unshaded modules. As a result, mismatch losses occur. Bypass diodes can prevent mismatch losses of this type. (2) can be used to compute the current flow via the bypass diode. where $I_{pv}$ is the Photocurrent, $I_{sat}$ is the reverse bias saturation current of a diode, $N_s$ is the number of PV cells linked in series on the given PV module, $q$ is the constant charge of electrons (1.60217 10-19C), $k$ is the Boltzmann constant (1.38065 10-23J/K), $T$ is the PN junction temperature, $R_s$ series resistance, and $R_p$ shunt resistance.

$$I_s = I_{pv} - I_{sat}\left[\exp\left(q\frac{V_s + I_s R_s}{N_s K T \eta}\right) - 1\right] - \frac{V_s + I_s R_s}{R_p} + I_{bp} \quad (1)$$

$$I_{bp} = I_{sat,bp}\left[e^{\left(q\frac{V_s}{KT\eta}\right)} - 1\right] \quad (2)$$

Figure 1 depicts the I-V and P-V characteristics of a PV string under PSCs. The PVs exhibit staircase-like I-V curves; however, their P-V and I-V characteristics reveal many peaks under PSCs, resulting in energy losses. As a result, investigating MPPT algorithms capable of managing PSCs is crucial. In response to this challenge posed by PSCs affecting PVs, we have developed an APSO algorithm tailored specifically for MPPT in such scenarios. Our proposed APSO algorithm is designed to address the complexities introduced by PSCs, allowing efficient and accurate tracking of the GMPP in PV arrays with fast settling time and high efficiency.

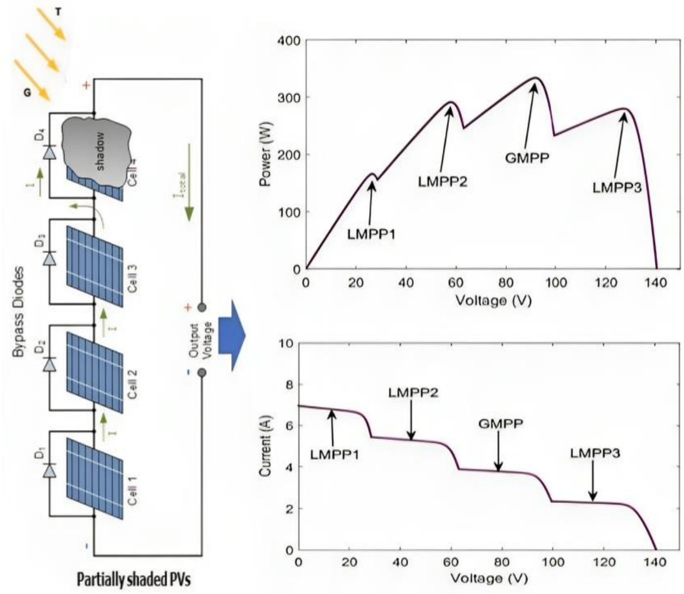



Figure 1. PVs under PSCs

### 2.2. DC-DC boost converter

DC-DC converters take various forms, with the Step-up chopper (Boost converter) being a key focus here, and its parameters are depicted in Table 1. Its primary role is elevating DC input voltage to match desired output levels. Comprising essential components like diodes, capacitors, a DC source, a switch, and inductors, as depicted in Figure 2, this converter acts as a vital interface harmonizing load and PV panel, enabling maximum power extraction [21].

The PWM pulse generator regulates duty cycles for operation between intervals $[\alpha T, T]$, the transistor is inactive. Here, $T$ is the static converter period, and α denotes the duty cycle. Model converter behavior, influenced by a K switch (MOSFET) controlled by the MPPT algorithm's duty cycle.

Table 1. The boost converter parameters

| Parameters | Value |
|---|---|
| Inductance (L) | 10 mH |
| Capacity ($C_{int}$) | 4 µF |
| Capacity ($C_{out}$) | 20 µF |
| Frequency (fs) | 50 kHz |

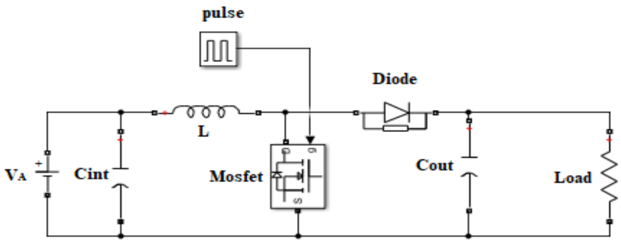



Figure 2. DC-DC boost converter

## 3. METHOD

### 3.1. Particle swarm optimization

PSO is an approach inspired by social behavior, specifically the collective movement of creatures such as bird flocking and fish schooling. PSO, proposed by Kennedy and Eberhart [22], is an optimization technique designed to identify the best solution in a search space by modeling particle social behavior. The fundamental principle of PSO involves the movement of individual particles within a defined search space to seek an optimal solution. PSO's core mechanics rely on two primary equations governing the behavior of particles: the velocity (3) and the position (4). Where: $x_i^{(k+1)}$ is the updated position and $x_i^{(k)}$ is the particle's previous position, $v_i^{(k)}$ is the initial velocity, while $v_i^{(k+1)}$ is the updated velocity, $x_{ibest}$ is each particle's individual best position, $x_{gbest}$ is top position in the swarm, $w$ is Inertia weight influencing velocity's impact, $C_1$ and $C_2$ are acceleration coefficients balancing personal and social experiences, and $r_1$ and $r_2$: random numbers enhancing exploration during updates.

$$v_i^{(k+1)} = wv_i^{(k)} + c_1 \times r_1\left(x_{ibest} - x_i^k\right) + c_2 \times r_2\left(x_{gbest} - x_i^k\right) \tag{3}$$

$$x_i^{(k+1)} = v_i^{(k+1)} + x_i^{(k)} \tag{4}$$

### 3.2. Advanced particle swarm optimization

The presented methodology is a sophisticated control strategy aimed at optimizing the performance of PVs, specifically in the presence of PSCs. The control methodology utilizes APSO principles to dynamically adjust the duty cycle of a Step-up chopper. This adjustment is crucial for increasing the system's power output by efficiently tracking and maintaining the GMPP with fast settling time under varying conditions. The methodology comprises the following sequential steps:

- Initialization: The code initializes several persistent variables, which are used to store and track various parameters and states throughout the algorithm.
- Main control loop: The algorithm operates in a loop, which is controlled by the variable $u$. $u$ ranges from 1 to 5 and is used to iterate through different aspects of the control strategy.
- Partial shading handling: For $u$ values from 1 to 4, the code checks whether the product of PV voltage ($V_{pv}$) and PV current ($I_{pv}$) is greater or less than the stored value in the p array at position u. If it is, the code updates $p(u)$ with the new value, and the corresponding $p_{best(u)}$ is updated with the current $d_{current}$ value.
- Duty cycle update: When $u$ is 1 to 4, the code returns a duty cycle value based on the values in the $dc$ array, and this value is assigned to$d_{current}$.
- Global best update: When $u$ equals 5, the code identifies the particle with the highest $p(u)$ (best power output), determines the corresponding $p_{best}$, and assigns this as the $g_{best}$. The algorithm then sets the $D$ value to the $g_{best}$, updates $d$ current, and proceeds to the velocity and duty cycle update phase.
- Velocity and duty cycle update: The code updates the velocity of each particle ($v$) using a PSO formula. It also updates the duty cycle values for each particle.
- Boundary constraints: The algorithm ensures that the duty cycle (dc) remains within a specific range (between 0.2 and 1).
- Termination: The loop continues until the counter reaches a certain threshold, and the algorithm returns the $d_{current}$ value.
- Helper functions: The algorithm includes two helper functions: update-velocity for calculating particle velocity and update-duty for updating the duty cycle while respecting boundaries.

The APSO algorithm is tailored for GMPPT in PVs as shown in Figure 3. The technique adapts boost converter duty cycles in real time, ensuring optimal system performance. Distinguished by adaptive personal and social experiences, it quickly converges toward the GMPP. It features an efficient adaptation mechanism under varying conditions, addressing the challenges posed by PSCs. Key innovations include personalized and social learning; it efficiently navigates the search space, enabling enhanced power generation efficiency. This technique outperforms previous algorithms in terms of flexibility, speed of convergence, effectiveness, and reliability to PSCs, Tuning Parameters: W=0.25, C1=1.2 and C2=1.2.

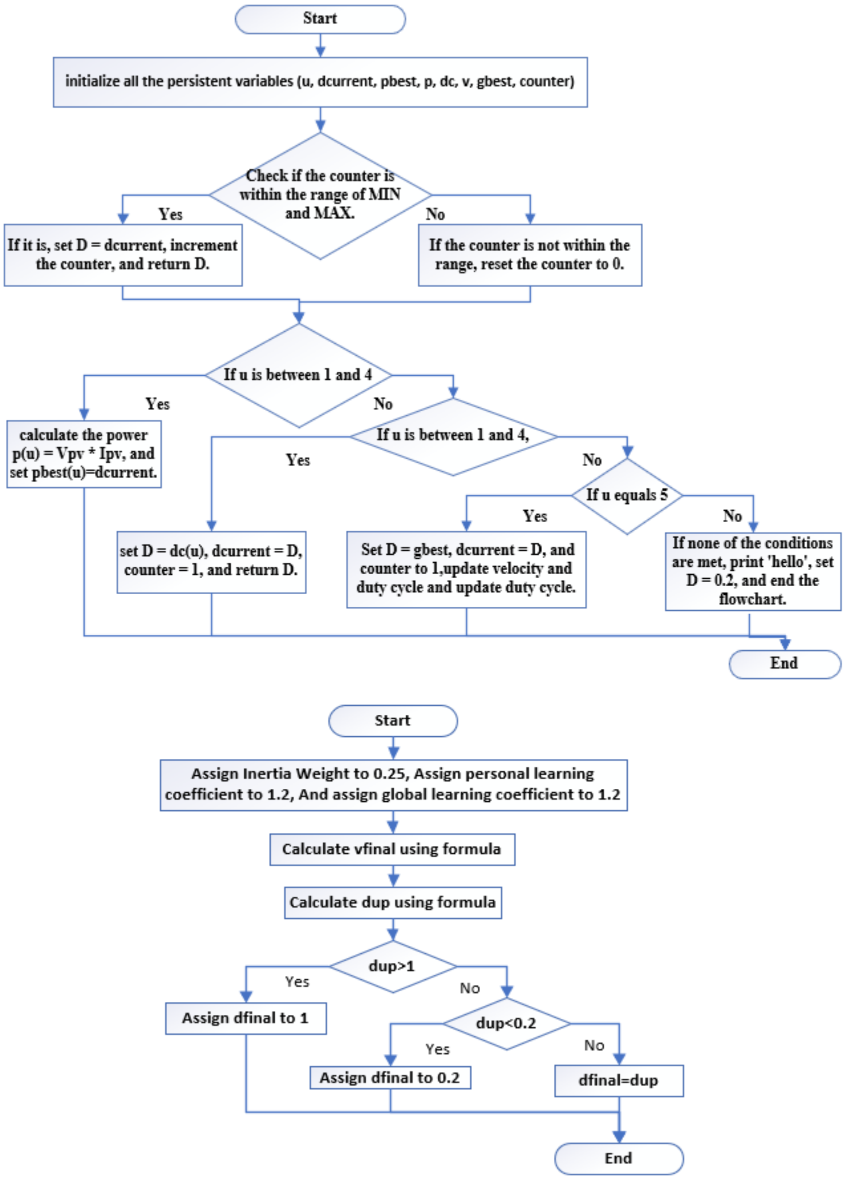



Figure 3. Flow chart of the APSO algorithm

## 4. RESULTS AND DISCUSSION

In this section, we assessed the efficacy of APSO within MATLAB/Simulink for maximizing power output and accelerating settling time in solar PV. We modeled the PV string using API156P200 PV panels to simulate the effects of PSCs. Employing a boost converter to manage the load; we adjusted the irradiance of the four series-connected PV panels as depicted in Figure 4, along with the boost converter illustrated in Figure 5. Simulations were conducted under constant temperature conditions of 25 °C. Comprehensive parameters for the solar PV modules are detailed in Table 2. This study delves into the effects of APSO on solar PV systems, specifically addressing its impact on power output and settling time. While earlier studies have explored many optimization techniques for solar PV, a gap exists in processing the explicit influence of partial shading conditions, in terms of combining efficiency, resilience, and fast settling time. In this study, we have aimed to address this gap through the design of APSO that combines efficiency, resilience, and fast settling time, as depicted in Table 3, which summarizes the simulation outcomes. Additionally, Table 4 compares the tracking efficiency, settling time, and other pertinent parameters with results obtained from four recent meta-heuristic techniques for a comprehensive assessment. This demonstrates the significant superiority of our proposed APSO over other techniques in terms of efficiency, fast settling time, and flexibility in combining them.

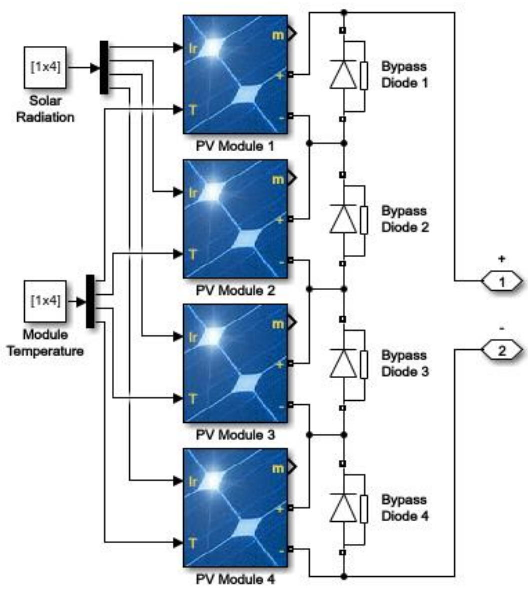



Figure 4. Four PV panels series-connected under PSCs

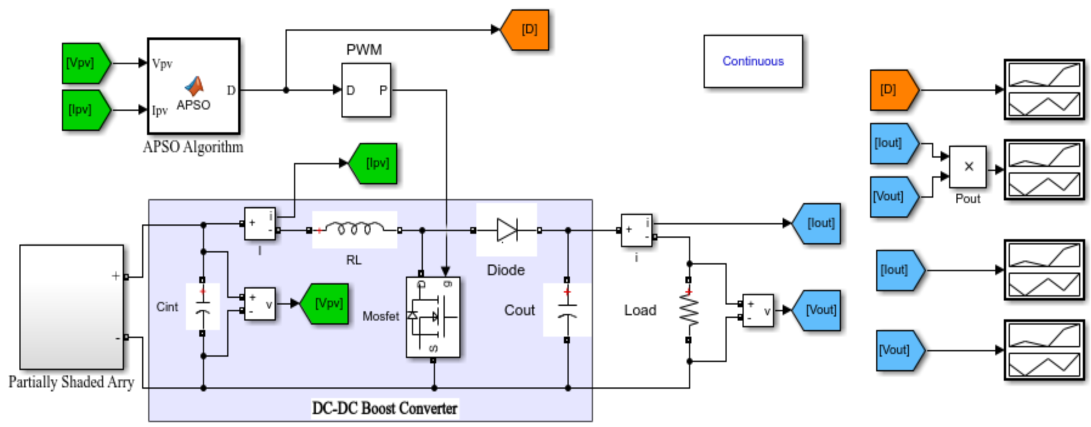



Figure 5. Four series-connected PV panels in diverse shading patterns managed by an APSO

Table 2. API156P200 PV module

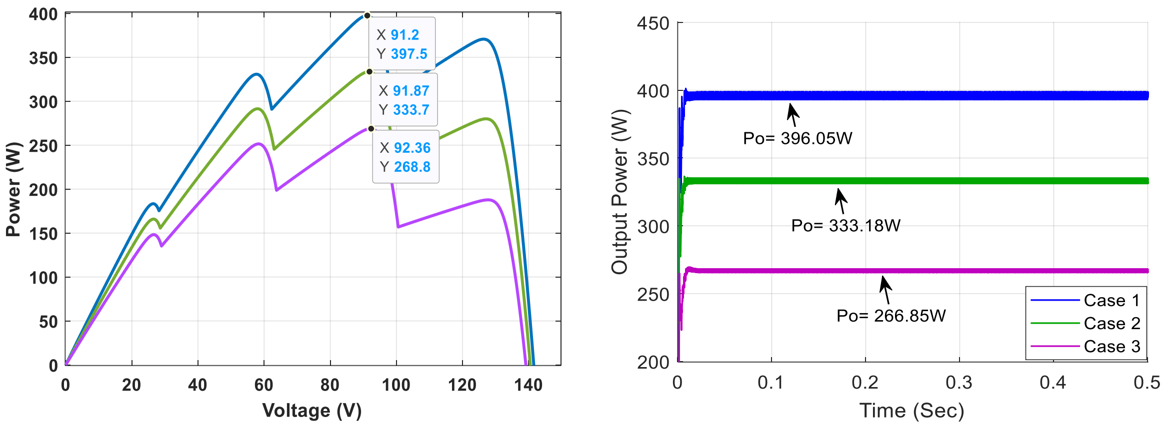
| Parameters | Value |
|---|---|
| Number of cells per module | 60 |
| $V_{oc}$ $(V)$ | 36 V |
| $I_{SC}$ $(A)$ | 7.75 A |
| $V_{Mpp}$ $(V)$ | 28.7 V |
| $I_{Mpp}$ $(A)$ | 6.97 A |
| $P_{Mpp}$ $(W)$ | 200.039 W |

### 4.1. The different shading patterns are examined in four different scenarios

To assess the effectiveness of our proposed technique, we carried out three simulations using MATLAB/Simulink software under various PSCs, depicted in Figure 6(a). Who illustrates the characteristic power-voltage plots, providing insights into the behavior of the photovoltaic strings under these specific PSCs. This assessment encompasses three different cases, each involving the solar panels experiencing four distinct irradiation levels, as depicted in Table 3. The outcomes for these cases are detailed in Table 3, with accompanying visuals in Figures 6(b) and 7. Figure 6(b) portrays the efficiency and stability, while Figure 7 illustrates the settling time (ST). During these simulations, the proposed APSO algorithm remarkably demonstrates superior tracking efficiency for the GMPP and fast settling time (ST) under PSCs. It achieves an impressive efficiency rate of 99.85% with a very rapid settling time of 0.01 seconds.

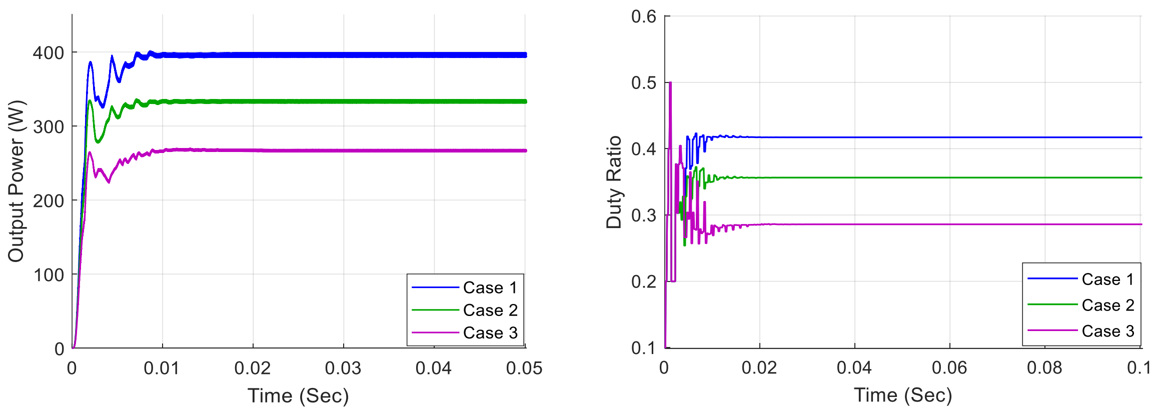
Table 3. Results of the three cases of studies

| Cases | Irradiance pattern ($\mathbf{w/m^2}$) | | | | Results | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | PV Module 1 | PV Module 2 | PV Module 3 | PV Module 4 | $P_{GMPP}(w)$ | $P_{out}(w)$ | Duty cycle (%) | Settling time (sec) | Efficiency (%) |
| Case 1 | 1,000 | 800 | 600 | 400 | 397.5 | 396.05 | 99.64 | 0.01 | 99.65 |
| Case 2 | 900 | 700 | 500 | 300 | 333.7 | 333.18 | 99.95 | 0.01 | 99.85 |
| Case 3 | 800 | 600 | 400 | 200 | 268.8 | 266.85 | 99.98 | 0.01 | 99.30 |




(a) (b)

Figure 6. Simulation results using APSO for the 3 cases: (a) PV module P-V curves for three different PSCs and (b) the output powers




(a) (b)

Figure 7. The zoomed images provide a closer look at two important aspects: (a) the settling time and (b) the duty ratio

### 4.2. Comparison of test results

The outcomes obtained from the proposed technique, the APSO algorithm, are compared with the five most recent meta-heuristic techniques: cat swarm optimization (CSO), cuckoo search (CS), marine predator algorithm (MPA), accelerated PSO (PSO), and modified PSO (MPSO). This comparative study specifically focuses on shading models using four photovoltaic panels with various irradiance levels. Notably, the P-V curve exhibits quadruple-peak values within the shading pattern. The assessment of this comparative study encompasses several aspects, including efficiency, accuracy, settling time, and reliability, as shown in Table 4. The remarkable results achieved by our proposed technique, the APSO algorithm, compared to other meta-heuristic optimization techniques, are evident regarding efficiency, accuracy, failure rate, steady-state oscillations, settling time and their combination. These results demonstrate the absolute superiority of APSO when employed for GMPPT in photovoltaic energy systems under PSCs.

Table 4. Comparison results between the APSO and five other meta-heuristics techniques under PSCs

| Techniques | CSO [23] | CS [24] | MPA [25] | PSO [13] | MPSO [26] | APSO |
|---|---|---|---|---|---|---|
| Efficiency (%) | 95.56 | 99.09 | 98.84 | 99 | 99 | 99.85 |
| Settling time (sec) | 0.05 | 0.16 | 0.04 | 2.5 | 0.3 | 0.01 |
| Tracking speed | Moderate | Slow | Moderate | Very slow | Slow | Fast |
| Tracking accuracy | Low | Good | Moderate | Good | Good | Excellent |

## 5. CONCLUSION

The Advanced particle swarm optimization algorithm, introduced in this research, represents a significant leap forward in addressing the complexities of optimizing photovoltaic systems under PSCs. APSO is tailored to achieve and sustain the GMPP and reach it quickly, combining effectiveness, accuracy, and stability speed by integrating persistent variables, boundary checks, and tracking system stat iterations and velocities. The results obtained from MATLAB/Simulink simulations and comparisons with recent meta-heuristic techniques, show that APSO consistently outperforms in computational efficiency, precision, stability, and fast settling time. Where the APSO technique achieves a tracking efficiency higher than 99% with a fast-settling time of less than 0.01 seconds for all test cases under PSCs. APSO's adaptability and rapid convergence towards optimal solutions position it as a key driver in advancing sustainable solar energy generation, fostering the development of more resilient and efficient PVs.

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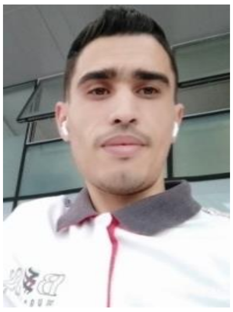
## BIOGRAPHIES OF AUTHORS



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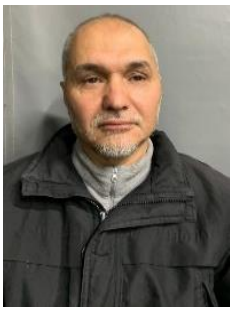

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