Maximizing Solar Panel Efficiency in Partial Shade: The Improved POA Solution for MPPT

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***Abstract*—This paper presents an innovative approach to improving Maximum Power Point Tracking (MPPT) in solar photovoltaic (PV) systems affected by partial shading, a common challenge that significantly reduces efficiency. Our research focuses on enhancing the Pelican Optimization Algorithm (POA), a promising tool in solar energy optimization, to better tackle the efficiency drop observed under shaded conditions. The enhancements to the POA involve the integration of advanced adaptive mechanisms that enable more precise response to the fluctuating irradiance patterns typical of partially shaded environments. This revised version of the POA demonstrates remarkable adaptability and precision in identifying and tracking the maximum power point, significantly outperforming its original iteration. The methodology of this study encompasses a series of rigorous simulations and real-world testing scenarios, designed to evaluate the POA's performance under various degrees and patterns of shading. The results show a notable improvement in efficiency, with the enhanced POA maintaining high levels of energy capture even in suboptimal sunlight conditions. Additionally, the improved algorithm exhibits robustness against the rapid changes in irradiance, which is characteristic of partially shaded solar PV systems. Our findings underscore the potential of the enhanced POA as a robust, adaptive solution for optimizing solar energy collection, offering significant benefits for solar installations in geographies prone to shading. This work not only contributes to the field of renewable energy optimization but also provides valuable insights for the development of more resilient and efficient solar energy systems.**

Keywords*—*Pelican Optimization Algorithm (POA); Maximum Power Point Tracking (MPPT); Solar Photovoltaic Systems; Partial Shading

I. INTRODUCTION

The rising global demand for energy, coupled with the escalating costs of fossil fuels and a growing awareness of environmental concerns, has spurred significant enthusiasm among numerous nations to shift towards renewable energy sources as a means to fulfill their energy requirements [1]. Renewable energy, encompassing wind energy, solar energy, and biomass/biogas, is gaining popularity across various domains, including robotics, domestic use, and industrial applications [2], [3]. Solar photovoltaic (PV) systems are becoming an increasingly popular option for the generation of electricity due to the numerous benefits associated with them [4]. These benefits include the fact that they are friendly to the environment, do not contain any moving parts, call for a low level of maintenance, do not generate any noise, have low running costs, and are simple to install. However, the low operational efficiency of PV systems, caused by the nonlinearity in their features and the variable environmental circumstances, presents a significant technological obstacle for their development. The occurrence of the phenomenon often denoted as partial shading exerts a notable influence on the total electricity production of photovoltaic (PV) systems [5], [6]. The Pelican Optimization Algorithm (POA) has emerged as a potentially useful tool for boosting the performance of photovoltaic (PV) systems, specifically in the domain of Maximum Power Point Tracking (MPPT). This is due to the fact that the Pelican Optimization Algorithm (POA) was developed by the Pelican Group, which is taking place in the midst of this shift in the energy sector. As the demand for solar PV systems continues to rise, the need for efficient MPPT techniques becomes imperative [7], [8], [9], [10]. POA, with its innovative technique that takes inspiration from the natural hunting habit of pelicans, holds the potential to address the intricate challenges posed by dynamic solar conditions, including changing solar irradiance and partial shading [11]. In the realm of photovoltaic systems, numerous effective techniques, such as hill-climbing (HC), perturb and observe (P&O), and incremental conductance (INC), among others, are available for achieving maximum power [12],[13],[14],[15]. Methods based on artificial intelligence (AI) are used to determine the maximum power point (MPP) of photovoltaic solar power when they encounter varying degrees of partial shading. These methods include neural networks, genetic algorithms, adaptive neuro-fuzzy inference systems (ANFIS), and fuzzy logic ([16], [17]. Beyond the previously mentioned approaches, a range of innovative bio-inspired and nature-mimicking algorithms have emerged for MPPT. These techniques include methodologies like Firefly Optimization, Artificial Bee Swarm Optimization (ABSO), Cuckoo Search, and the Flower Pollination Algorithm (FPA) [18], [19]. The ever-increasing global energy demand, coupled with concerns about environmental sustainability, underscores the urgency of developing robust and efficient MPPT techniques for solar PV systems [20]. This article explores the evolution and adaptation of the Pelican Optimization Algorithm (POA) to address these challenges and enhance the optimization of PV systems under various operational scenarios. The integration of artificial intelligence and nature-inspired algorithms into MPPT strategies promises to revolutionize the efficiency and sustainability of solar energy harvesting. In this research, we introduce the Adaptive and Enhanced Pelican Optimization Algorithm (IPOA), a cutting-edge metaheuristic MPPT solution designed to optimize photovoltaic (PV) systems [21], [22]. Our focus centers on enhancing energy extraction from PV systems, particularly under dynamic conditions, including partial shading [23], [24].

A. Research Questions

- How effective are current MPPT techniques in optimizing PV system performance under varying shading conditions?
- What are the potential performance improvements achievable through novel optimization algorithms like the Improved Pelican Optimization Algorithm (IPOA)?

B. Research Objectives

Develop and evaluate the IPOA algorithm for enhancing MPPT performance under dynamic solar conditions. Investigate the effectiveness of IPOA compared to existing MPPT techniques. Demonstrate the applicability of IPOA across diverse operational scenarios.

C. Related Work

Prior research in the field of solar photovoltaic (PV) systems has explored various methods for maximizing energy harvest, particularly under challenging conditions such as partial shading. Traditional maximum power point tracking (MPPT) techniques, including hill-climbing (HC), perturb and observe (P&O), and incremental conductance (INC), have laid the foundation for system optimization but may struggle to adapt to dynamic environmental factors. Additionally, researchers have investigated the integration of artificial intelligence (AI)-based methods such as neural networks and genetic algorithms to enhance MPPT performance. Bio-inspired algorithms like Firefly Optimization and Artificial Bee Swarm Optimization (ABSO) have also emerged as promising approaches. While these techniques offer valuable insights, there remains a need for more robust and adaptive optimization strategies to address the complexities of PV system operation, particularly in the presence of partial shading.

D. Organization of the Document

This paper is structured as follows: Section I introduces the research problem, questions, and objectives. Section II discusses PV system modeling under partially shaded scenarios. Section III presents the Pelican Optimization Algorithm (POA). Section IV introduces the Improved Pelican Optimization Algorithm (IPOA). Section V presents the simulation setup and empirical results. Finally, Section VI concludes the paper.

II. System Modeling

The power produced by a PV array is directly linked to its output voltage, making the maximization of this voltage essential for optimizing the arrays overall power generation. Achieving this optimization is made possible through the utilization of a DC-DC converter, which controls the output voltage of the PV array. Techniques such as pulse width modulation (PWM) come into play in order to make precise adjustments to the DC-link voltage, which is necessary in order to maintain a stable output from the DC-DC converter. During this time, a boost converter has been invisibly incorporated into the photovoltaic system in order to control the terminal voltage. Before the photovoltaic system can be linked to the public electricity grid, it is necessary to begin by synchronizing the output of the boost converter with a one-phase pulse width modulation inverter.

A. Features of a PV Power System

The standard electrical representation of a PV cell featuring a single diode incorporates elements like a photocurrent source with an anti-parallel diode, a shunt resistor, a series resistor connected across the load, and several other components. This model encompasses a few additional elements as well Fig. 1 illustrates the schematic diagram representing he corresponding circuit of a PV cell with a single diode Guidelines for selecting and were used to increase solar PV module modeling accuracy.

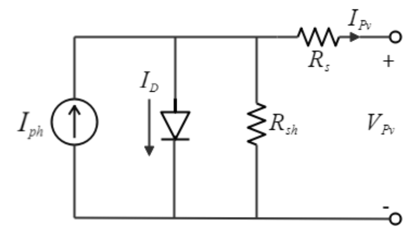

Fig. 1. Photovoltaic module's single-diode representation.

The output current of the PV cell, I_{Pv} can be calculated as follows:

$$I_{ph} = I_{Pv} - I_D - \frac{V_{Pv} + R_s * I_{Pv}}{R_{sh}} \tag{1}$$

$$I_D = I_O \left(e^{V_D / \alpha V_T} - 1 \right) \tag{2}$$

And at last, the equation for the current flowing out of a PV module is found, as shown below:

$$I_{Pv} = I_{ph} N_{pp} - I_O N_{pr} \left\{ \exp\left[\left(\frac{V_{PV} + I_{Pv} R_S \left(\frac{N_{sr}}{N_{pr}} \right)}{m V_t N_{sr}} \right) - 1 \right] \right\} - \left(\frac{V_{PV} + I_{PV} R_s \left(\frac{N_{sr}}{N_{pr}} \right)}{R_{sh} \left(\frac{N_{sr}}{N_{pr}} \right)} \right) \tag{3}$$

This graph, Fig. 2, depicts the power-voltage (P-V) characteristics of a PV system (photovoltaic system) under ideal conditions, when there is no partial shadowing present. The PV system's voltage and power output are shown on the x- and y-axes, respectively. As solar irradiance is constant and shading effects are insignificant, the graph has a smooth, single-peaked curve. In this curve, there is a one-to-one correspondence between voltage and power. The P-V curve of a PV module shows an increase in the module's power output in response to an increase in voltage. Under this optimum circumstance, the photovoltaic (PV) system performs at its (MPP), also known as the curve peak. The MPP is designed to generate the largest amount of power while simultaneously maximizing both its efficiency and its output of energy. Establishing a PV system performance baseline requires understanding this graph's behavior under non-shaded conditions. It is used to evaluate how the system responds to dynamic solar circumstances and partial shadowing, as discussed in later sections.

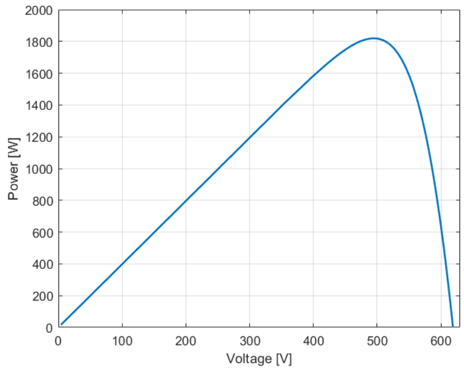

Fig. 2. Optimizing solar cell efficiency: P-V characteristics.

B. Partial Shading Phenomenon in PV Arrays

Partial shading, a common occurrence in photovoltaic (PV) systems due to factors such as passing clouds, adjacent structures, and vegetation, significantly influences energy generation and system efficiency. To appreciate the dynamic behavior of PV modules under such situations and to come up with appropriate techniques for maximum power point tracking (MPPT), accurate modeling of partial shading is absolutely necessary. The employment of mathematical models, such as the single-diode model or the two-diode model, is a method that is commonly put into practice for the purpose of modeling partial shading. Additionally, they incorporate factors like shading patterns, module configuration, and environmental variables, providing a foundation for simulating partial shading scenarios that become bottlenecks that limit the entire system's power generation. This can lead to significant power losses and decreased overall efficiency. To mitigate the impact of partial shading, advanced maximum power point tracking (MPPT) algorithms and innovative circuit designs are employed to dynamically adjust the operating points of individual cells or modules.

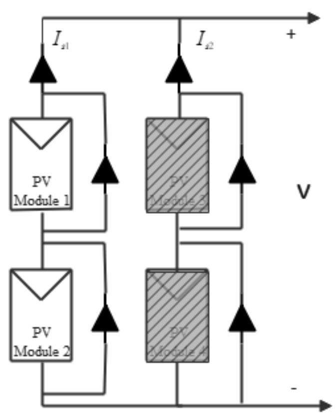

Fig. 3. Operational characteristics of a solar PV array.

By managing the voltage and current levels, these techniques help optimize the power output, ensuring the PV system remains efficient even under challenging shading conditions. Despite these advancements, careful design and installation of PV arrays in locations with minimal shading remain crucial to harnessing the maximum solar energy potential and achieving optimal performance. Fig. 3 shows operational characteristics of a solar PV array.

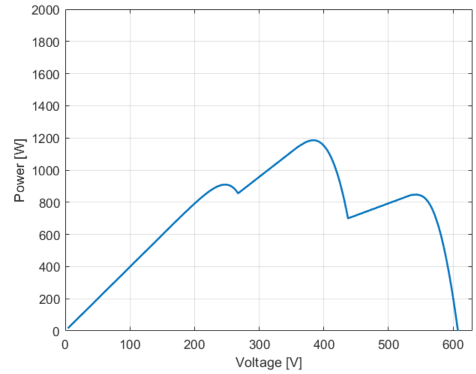

Fig. 4. Optimizing PV cell operation in partial shading: P-V characteristics.

This graph, Fig. 4, unveils the intriguing behavior of a photovoltaic (PV) system when confronted with partial shading, a common real-world scenario. It presents the relationship between the PV system's voltage and power output, with voltage on the x-axis and power on the y-axis. In contrast to the smooth curve observed under ideal, non-shaded conditions, this graph exhibits a distinctive pattern with multiple peaks and a more intricate structure. Partial shadowing causes dynamic solar irradiance fluctuations, reducing sunlight to some PV module portions. The P-V curve fragments show several local peaks instead of a global maximum. Each peak is a localized maximum

III. Pelican Optimization Algorithm

Before the Pelican Optimization Algorithm (POA), a novel stochastic optimization method is inspired by the hunting behavior of pelicans. POA employs pelican-like agents to search for optimal solutions in optimization problems across various scientific fields. The algorithm's unique design combines efficient exploitation for unimodal functions and effective exploration for multimodal functions. The mathematical model of POA is presented, and its performance is assessed on different objective functions.

The proof of POA's supremacy lies in the fact that it outperformed eight well-known metaheuristic algorithms in a head-to-head competition. The fact that it is able to find a middle ground between exploration and exploitation makes it a potentially useful strategy for optimizing theoretical as well as real-world problems. Advancing towards the Prey (Exploration Phase): In the exploration phase of POA that can be metaphorically likened to pelicans scanning the water's surface for prey, the algorithm seeks to explore the solution space in search of potential optimal solutions.

This phase involves the following steps: Explore the Prey's Location: Similar to pelicans surveying the water for prey, the algorithm initially assesses the current state of the solution space. It evaluates the fitness of existing solutions and identifies areas that show promise for improved solutions. Move towards a Specific Spot: POA doesn't randomly explore the solution space but strategically moves toward specific areas based on the evaluation of existing solutions. This targeted approach reduces computational overhead and accelerates the search for optimal solutions. Winning on Water Surface (Exploitation Phase): The exploitation phase in POA can be likened to pelican's effectively herding and capturing prey. It focuses on refining and maximizing the exploitation of promising solutions discovered during the exploration phase: Prey Herding: Just as pelicans cooperate to encircle and herd prey towards shallow waters, POA concentrates on refining promising solutions. It identifies the most favorable solutions found during the exploration phase and herds them toward the optimal region of the solution space. Diving for Prey: In this phase, the algorithm dives deeper into the most promising solution areas, refining and optimizing them further. This is akin to pelicans diving to capture their prey efficiently. POA employs specialized optimization techniques to fine-tune solutions, maximizing their fitness and approaching the true optimum.

The Pelican Optimization Algorithm (POA) described here is a population-based approach, with the individual pelicans themselves serving as the working elements of the algorithm. Each individual within a population-based algorithm represents a candidate answer, providing guidance on what to set optimization problem variables to base on where they are in the search space. In the first step, members of the population are randomly selected between the problem's bottom and upper boundaries.

$$u_{i,j} = LB_j + rand * \left(UB_j - LB_j\right) \tag{4}$$

The Pelican Optimization Algorithm (POA) described here is a population-based approach, with the individual pelicans themselves serving as the working elements of the algorithm. Each individual within,

With i: Search Agent (i = 1,2,3,4 ...N) N: Population of Search Agents D: Design Variable According to Equation (10), a matrix that is referred to as the population matrix can be used to describe the individuals that make up the planned POA population. In this matrix, each row denotes a different set of values

Exploration phase:

$$u_{i,j} = \begin{cases} u_{i,j} + rand * \left(P_j - I * u_{i,j}\right), & Fitness_p < Fitness_i \\ u_{i,j} + rand * \left(u_{i,j} - P_j\right), & otherwise \end{cases} \tag{5}$$

Exploitation phase:

$$u_{i,j} = \begin{cases} u_{i,j} + rand * \left(P_j - I * u_{i,j}\right), & Fitness_p < Fitness_i \\ u_{i,j} + rand * \left(u_{i,j} - P_j\right), & otherwise \end{cases} \tag{6}$$

The iterative process that the Pelican Optimization Algorithm (POA) goes through is depicted graphically in the algorithm's flowchart. It starts with an initialization phase that mimics the searching behavior of pelicans for prospective solutions across the solution space. This is done within the context of the solution space. After that, the algorithm enters a phase known as exploitation, during which it focuses its efforts on potential solutions. This phase is analogous to the process by which pelicans herd their prey before swooping in for the kill. Iterations will continue until a predetermined stopping condition is met, during which time the algorithm will dynamically adjust in order to analyze and select the best possible solutions. The flowchart provides a visual representation of the algorithm's exploration and exploitation phases, demonstrating the algorithm's flexibility in terms of its ability to solve difficult optimization issues.

IV. Improved Pelican Optimization Algorithm

The Pelican Optimization Algorithm (POA) has shown promise in the realm of solar Maximum Power Point Tracking (MPPT), a critical aspect of enhancing the efficiency of solar photovoltaic (PV) systems. However, one of the key challenges faced with the original POA is its tendency to require a substantial number of iterations and considerable time to converge to the optimal MPPT solution. This often results in a less-than-ideal response time, particularly under dynamic environmental conditions such as variable solar irradiance and partial shading, which are common in real-world solar installations. To address these limitations, this paper introduces a significant improvement to the original POA. The core concept of this enhancement revolves around optimizing the algorithm's ability to find the most effective MPPT solution more rapidly and with greater accuracy. By refining the POA's search and convergence mechanisms, the goal is to reduce the iteration count significantly while ensuring that the error margin approaches zero. This improved version of POA is designed to offer a faster, more precise and more reliable approach to MPPT, especially in scenarios where rapid changes in solar irradiance due to partial shading can drastically affect the performance of solar PV systems. The following sections will detail the specific modifications made to the original POA, explain the mechanics of the improved algorithm, and discuss the advantages of these enhancements in the context of solar MPPT.

Idea Pelicans are renowned for their distinctive group behaviors, which are critical to their survival and efficiency in the wild. These birds often hunt in cohesive groups, skillfully coordinating their efforts to maximize the chances of a successful catch. Notably, they are observed flying in a 'V' formation, a strategic arrangement that optimizes aerodynamics and energy expenditure. Within this formation, a clear hierarchy of leading and following emerges, where one or more pelicans take the lead, and the others align their movements accordingly. This harmonious interplay of leadership and teamwork in pelicans serves as a fascinating parallel to our proposed improvements in the Pelican Optimization Algorithm. By mirroring these natural strategies, we aim to enhance the algorithm's efficacy in solving complex problems. The core idea is to select leading candidates—akin to the leading pelicans with the most successful hunting positions—and use their 'positions' or algorithmic solutions to guide the rest of the group. This approach allows for a more dynamic and efficient updating of positions within the algorithm, ensuring quicker convergence to optimal solutions, much like pelicans efficiently adjusting their flight patterns in response to their leaders. This biomimicry not only enriches the POA with a more robust search mechanism but also significantly reduces the computational time and iterations needed to reach the most effective solutions in real-world applications, such as solar photovoltaic systems. The Improved Pelican Optimization Algorithm (IPOA) takes inspiration from the pelican's strategic hunting methods to enhance Maximum Power Point Tracking (MPPT) in photovoltaic systems. By selecting two high-quality candidates, akin to pelicans identifying rich fishing spots, the IPOA maintains diversity and prevents premature convergence on suboptimal solutions. These candidates guide the search process, ensuring a balanced exploration and exploitation of the solution space, leading to faster and more reliable convergence. This approach enhances the IPOA's adaptability and robustness, particularly in dynamic environments like partial shading in solar arrays, making it an effective tool for optimizing energy harvest in solar PV systems. Enhancement 1: Dual Leading Candidates Selection in the first significant enhancement to the Pelican Optimization Algorithm (POA), we introduce the concept of selecting dual leading candidates, termed as 'Alpha' and 'Beta.' This enhancement is inspired by the natural hierarchy observed in pelican groups during their hunting expeditions, where typically, one or two pelicans assume the leadership role

Mechanism of Selection:

The algorithm identifies two candidates with the most optimal positions in the search space, analogous to pelicans with the most successful catch.

These positions are determined based on the maximization criteria relevant to the problem at hand, such as the highest energy output in MPPT applications for solar PV systems.

'Alpha' represents the candidate with the absolute best position (maximum solution), while 'Beta' is identified as the candidate with the second-best position.

This dual selection strategy aims to ensure a more diverse and robust search process, mitigating the risk of the algorithm prematurely converging to local optima.

Enhancement 2: Group Position Update Mechanism

- The Group Position Update Mechanism is inspired by the adaptive and responsive flight patterns of pelicans in a group, particularly how they adjust their positions in relation to the leaders.
- This mechanism is implemented through a set of three equations. Each equation plays a distinct role in guiding the movement of the candidate solutions in the search space.

First Equation:

The position of the α candidate is updated by:

$$X_i^{\alpha} = R_{\alpha}.\left(1-\frac{t}{T}\right).(2.r-1).x_i \tag{7}$$

This is followed by calculating the new potential position for the α candidate:

$$X_i^{new,\alpha} = P^{\alpha} + X_i^{\alpha} \tag{8}$$

For β candidate:

Similarly, for the β candidate, the position is updated by:

$$X_i^{\beta} = R_{\beta}.\left(1-\frac{t}{T}\right).(2.r-1).x_i \tag{9}$$

And the new potential position for the β candidate is:

$$X_i^{new,\beta} = P^{\beta} + X_i^{\beta} \tag{10}$$

Final Update Step:

Finally, the updated position for the next iteration, which incorporates information from both the α and β candidates, is calculated by averaging their new potential positions:

$$X_i^{update} = \frac{X_i^{new,\alpha} + X_i^{new,\beta}}{2} \tag{11}$$

In these equations:

- X_i^{α} and X_i^{β} represent the new positions for the α and β candidates, respectively.
- R_{α} and R_{β} are coefficients that adjust the step size for the α and β candidates.
- t Denotes the current iteration, and T represents the total number of iterations.
- r Is a random number between 0 and 1.
- x_i Is the current position.
- $x_i^{new,\alpha}$ and $x_i^{new,\beta}$ are the new potential positions for the α and β candidates after moving towards or away from the current position.
- x_i^{update} Is the final updated position for the next iteration, averaged from the α and β candidate positions.

These equations form the iterative update mechanism of IPOA, where the positions of candidates α and β are adjusted according to the optimization process, and their average is used to update the solution in search of the optimal maximum power point.

The introduction of the Dual Leading Candidates Selection in the Improved Pelican Optimization Algorithm symbolizes a significant leap toward mimicking the collaborative and efficient hunting strategies of pelicans. This enhancement is not just a theoretical modification but a practical solution aimed at addressing real-world challenges in optimization, particularly in the dynamic and often unpredictable domain of solar energy harvesting.

V. Result and Discussion

In this section, we present a comparative analysis focusing on the performance of the Improved Pelican Optimization Algorithm (POA) against the original POA, Particle Swarm Optimization (PSO). The primary metric for comparison is the mean power output achieved by each algorithm in the context of Maximum Power Point Tracking (MPPT) under partial shading conditions in solar photovoltaic (PV) systems. The simulations were designed to replicate realistic solar energy scenarios, enabling a thorough analysis of IPOA's optimization effectiveness. In the course of our study, a specific set of parameters was utilized to fine-tune the IPOA's performance. The chosen parameters were critical in guiding the algorithm towards optimal solutions efficiently. The table below outlines the key parameters and their respective values, which were instrumental in the simulation and testing phases of our research: research:

Table I provides a comprehensive overview of the fundamental parameters crucial to our analysis, accompanied by their respective values. This detailed breakdown serves as a foundational reference for understanding the intricacies of our study.

TABLE I. PARAMETERS OF THE PELICAN OPTIMIZATION ALGORITHM (IPOA)

Parameter	Symbol	Value
Pelican Population Size	N	10
Maximum Generations	T	50
Search Radius alpha	R_α	0.5
Search Radius beta	R_β	0.35
Coefficients	r	$random\ vector\ in\ [0,1]$

The results, as demonstrated by the table, indicate a tangible improvement in MPPT efficiency when using the IPOA. The parameter settings were meticulously adjusted to align with the dynamic behavior of partial shading effects on solar panels, ensuring that the algorithm could adapt and respond effectively. The careful calibration of these parameters was pivotal in achieving the enhanced outcomes presented in this study.

1) Experiment setup: Briefly describe the experimental setup, including the solar PV system model used, the specific conditions under which partial shading was simulated, and any relevant parameters that were constant across all tests.

Outline the criteria used for the comparison, such as the number of iterations, the environmental conditions simulated, and any specific features of the algorithms that were evaluated.

2) Objective of the comparison: The main objective of this comparative study is to evaluate the effectiveness of the Improved POA in optimizing the power output of solar PV systems under partial shading, as compared to the original POA, PSO.

This comparison aims to highlight the advancements made in the Improved POA, specifically in terms of its efficiency, accuracy, and speed in converging to the optimal solution for MPPT.

This introduction sets the stage for a detailed presentation of your results, providing clarity on the purpose, methodology, and objectives of your comparative analysis. It should help readers understand the context in which your findings were obtained and the metrics used to evaluate the performance of the Improved POA against other algorithms.

Case 1: ir1=1000 W/m², ir2=1000 W/m²; ir3=400 W/m²; ir4=800 W/m²

The results, as evidenced by the table (see Table II), reveal a significant enhancement in MPPT efficiency when implementing the IPOA algorithm.

TABLE II. MPPT EFFICIENCY: PSO, POA, AND IPOA COMPARISON (SCEBNARIO1)

	PSO	POA	IPOA
1	749,96	837,54	1047,91
2	814,52	861,95	1115,65
3	941,00	997,50	1151,82
4	1026,33	1010,06	1179,10
5	1075,35	1022,07	1179,90
6	1117,73	1059,40	1180,36
7	1165,04	1059,52	1182,56
8	1173,40	1069,61	1184,11
9	1149,18	1099,75	1184,34
10	1168,90	1135,63	1184,34
11	1180,60	1146,60	1185,19
12	1180,44	1146,60	1185,19
13	1180,05	1150,79	1185,19
14	1183,70	1150,79	1185,31
15	1184,26	1150,79	1185,31
16	1183,42	1150,79	1185,31
17	1182,53	1157,65	1185,431
18	1184,90	1158,40	1185,44
19	1184,56	1158,72	1185,44
20	1185,38	1163,90	1185,44
21	1184,99	1168,36	1185,45
22	1184,58	1168,36	1185,48
23	1184,83	1168,35	1185,48
24	1185,44	1171,06	1185,48
25	1185,20	1171,47	1185,48
26	1185,34	1172,79	1185,48
27	1185,52	1172,79	1185,48
28	1185,44	1173,90	1185,48
29	1185,44	1173,90	1185,48
30	1185,46	1173,90	1185,48
31	1185,51	1173,90	1185,48
32	1185,49	1173,90	1185,48
33	1185,49	1174,11	1185,48
34	1185,49	1174,11	1185,48
35	1185,51	1175,41	1185,48
36	1185,50	1180,26	1185,48
37	1185,53	1180,48	1185,48
38	1185,48	1181,61	1185,483
39	1185,51	1181,61	1185,48
40	1185,51	1181,61	1185,48
41	1185,47	1182,33	1185,48
42	1185,47	1184,27	1185,50
43	1185,49	1184,44	1185,50
44	1185,53	1184,73	1185,50
45	1185,49	1184,73	1185,50
46	1185,45	1185,08	1185,50
47	1185,49	1185,16	1185,50
48	1185,53	1185,16	1185,50
49	1185,47	1185,26	1185,508
50	1185,48	1185,26	1185,50

The initial quantitative data sets the stage for a deeper exploration of the results, with, Fig. 5, providing an initial insight into our findings.

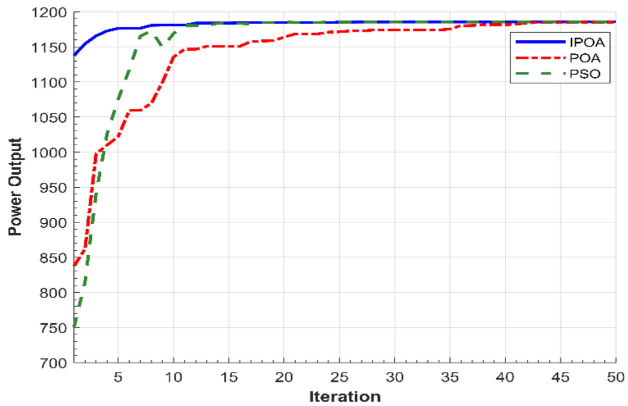

Fig. 5. Comparative performance of IPOA, PSO, and POA under partial shading conditions (scenario 1).

Following this introductory data, the ensuing figure and table offer a comprehensive comparison of the error margins encountered in Maximum Power Point Tracking (MPPT) using IPOA. These visual representations delve deeper into the nuances of our findings, providing a detailed examination of IPOA's performance in optimizing photovoltaic systems.

Additionally, we present Table III below that compares key performance indicators, offering a comprehensive insight into the effectiveness of different methodologies.

TABLE III. PERFORMANCE METRICS: PSO, POA, IPOA (SCENARIO 1)

	Mean Power Output	Maximum Power Output	Standard Deviation
PSO	1155.47	1185.54	88.79
POA	1140.53	1185.27	76.37
IPOA	1182.03	1185.58	8.53

Analysis:

- IPOA shows the highest mean power output, suggesting better average performance across all iterations.
- The maximum power outputs of all algorithms are very close, with IPOA marginally leading.
- The standard deviation is significantly lower for IPOA compared to PSO and POA, indicating that IPOA has the most consistent performance across iterations.

Having evaluated the overall efficiency and consistency of the algorithms, we now shift our focus to a detailed error analysis. The ensuing figure and table provide an in-depth comparison of the error margins in MPPT for IPOA versus PSO and POA. This examination is crucial to understand the precision and reliability of each algorithm under variable solar conditions.

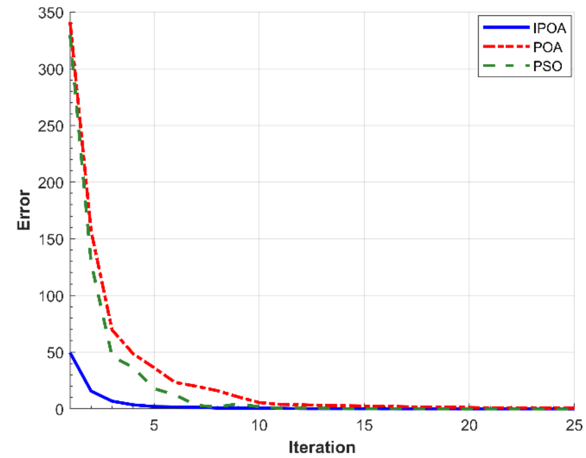

Fig. 6. Error analysis in MPPT: IPOA vs. PSO and POA (scenario1).

As the error lines diminish at a more gradual pace, it indicates that the algorithm (see Fig. 6) is reaching a state of stabilization, progressively converging towards the optimal parameters.

TABLE IV. ERROR METRICS: IPOA VS. POA AND PSO (SCENARIO1)

	MAE	MSE	RE
IPOA vs POA	41.50	6291.25	4.14%
IPOA vs PSO	26.73	7054.30	3.06%

The presence of a discernible error fluctuation suggests that the IPOA entities engaged in a diverse exploration (see Table IV) of the solution space.

Interpretation:

- MAE (Mean Absolute Error): On average, the power output of IPOA differs from POA by about 41.50 units and from PSO by about 26.73 units. The lower MAE for PSO suggests that IPOA's results are closer to PSO's results on average than to POA's.
- MSE (Mean Squared Error): The MSE values are higher, indicating that there are instances where the differences in power outputs are quite large. The higher MSE for IPOA vs PSO indicates more significant deviations when compared to PSO than to POA.
- RE (Relative Error): Indicates that on average, the IPOA's power output is about 4.14% different from POA's and 3.06% different from PSO's. This gives an idea of the error in terms of proportion to the compared algorithm's output.

These errors provide insight into how closely IPOA's performance aligns with that of POA and PSO, with a particular focus on the consistency and magnitude of the differences between their outputs.

Case 2: ir1=900 W/m², ir2=900 W/m²; ir3=600 W/m²; ir4=650 W/m²

TABLE V. MPPT EFFICIENCY: PSO, POA, AND IPOA COMPARISON (SCEBNARIO2)

	PSO	POA	IPOA
1	827,84	892,66	1116,85
2	894,83	920,17	1143,24
3	991,15	947,55	1174,72
4	1093,69	969,67	1220,74
5	1184,56	974,60	1235,29
6	1231,63	995,17	1235,29
7	1249,54	1036,32	1246,41
8	1248,10	1076,69	1253,04
9	1251,60	1113,67	1253,04
10	1253,34	1125,17	1253,45
11	1251,95	1157,98	1253,72
12	1252,56	1210,77	1253,72
13	1253,00	1219,67	1253,72
14	1253,37	1219,67	1253,72
15	1252,21	1240,70	1254,39
16	1253,88	1241,90	1254,39
17	1253,69	1243,44	1254,57
18	1253,85	1249,51	1254,57
19	1254,49	1249,51	1254,57
20	1254,13	1249,51	1254,74
21	1253,69	1249,55	1254,74
22	1254,57	1249,55	1254,74
23	1254,18	1250,17	1254,74
24	1253,93	1250,23	1254,80
25	1254,62	1250,23	1254,80
26	1254,19	1252,99	1254,80
27	1254,37	1252,99	1254,80
28	1254,80	1252,99	1254,80
29	1254,78	1252,99	1254,80
30	1254,66	1253,71	1254,80
31	1254,78	1253,71	1254,80
32	1254,90	1253,71	1254,80
33	1254,86	1253,71	1254,80
34	1254,80	1254,06	1254,84
35	1254,90	1254,06	1254,85
36	1254,89	1254,06	1254,85
37	1254,82	1254,16	1254,85
38	1254,82	1254,16	1254,85
39	1254,92	1254,16	1254,85
40	1254,90	1254,16	1254,85
41	1254,88	1254,16	1254,86
42	1254,91	1254,37	1254,87
43	1254,87	1254,45	1254,89
44	1254,84	1254,45	1254,91
45	1254,92	1254,56	1254,91
46	1254,91	1254,56	1254,91
47	1254,91	1254,56	1254,92
48	1254,92	1254,92	1254,94
49	1254,94	1254,92	1254,94
50	1254,91	1254,92	1254,95

In the second scenario, this quantitative data (see Table V) serves as an introductory glimpse into the observed trends and patterns, paving the way for a more detailed exploration in the subsequent result figures (see Fig. 7).

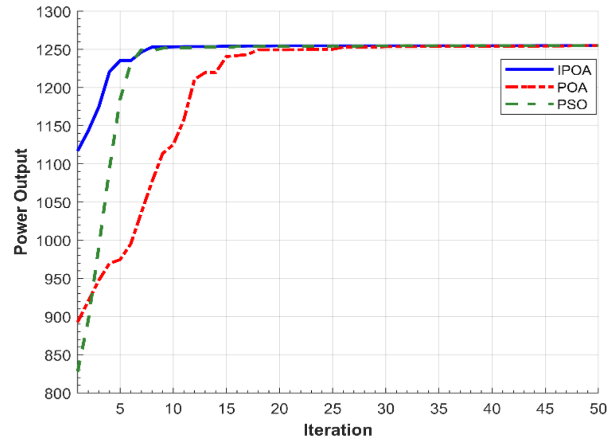

Fig. 7. Comparative performance of IPOA, PSO, and POA under partial shading conditions (scenario2).

Following this preliminary data, the subsequent figure and table offer a detailed comparison of the error margins encountered during MPPT with IPOA, providing a comprehensive analysis of its performance. Table VI shows the performance metrics of PSO, POA and IPOA.

TABLE VI. PERFORMANCE METRICS: PSO, POA, IPOA (SCENARIO 2)

	Mean Power Output	Maximum Power Output	Standard Deviation
PSO	1228.01	1254.94	87.72
POA	1198.71	1254.92	104.79
IPOA	1246.38	1254.94	27.23

Overall, IPOA demonstrates the best average performance and reliability, with consistent closeness to peak power output. POA, despite achieving similar peak performance, shows greater variability, potentially making it less reliable for consistent output. PSO's performance is intermediate in both average output and consistency. This analysis (see Fig. 8) highlights IPOA as the preferable choice for applications where average performance and reliability are key considerations.

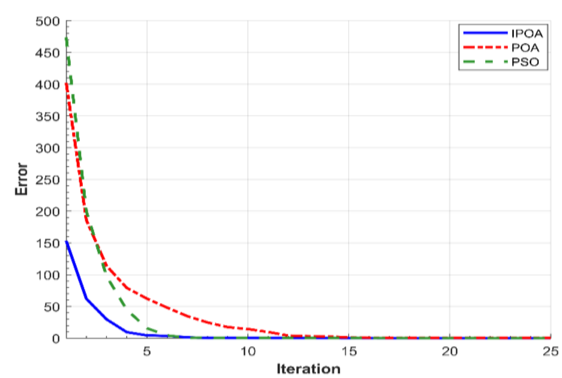

Fig. 8. Error analysis in MPPT: IPOA vs. PSO and POA (scenario2).

TABLE VII. ERROR METRICS: IPOA VS. POA AND PSO (SCENARIO2)

	MAE	MSE	RE
IPOA vs POA	47.67	9308.13	4.71%
IPOA vs PSO	18.51	3954.33	1.98%

There was a notable fluctuation in error, indicating a diverse exploration of the solution space by the IPOA entities. Table VII shows error metrics in Scenario 2.

Higher Average Output: IPOA has a greater mean power output, indicating better overall effectiveness. Peak Performance: Although all three algorithms achieve similar maximum outputs, IPOA maintains this peak more consistently, as shown by its lower standard deviation. Less Variability: IPOA's reduced variability implies more reliable and stable performance.

Consistent Peak Performance: IPOA, PSO, and POA all reach similar maximum power outputs, but IPOA does so with greater consistency, as evidenced by its lower standard deviation. Reduced Variability: The lower standard deviation for IPOA suggests more stable and reliable performance, with less fluctuation in power output. Faster Achievement of Optimal Values: IPOA is notably quicker in reaching optimal or best values compared to PSO and POA, an important feature in time-sensitive applications or where rapid convergence is essential.

Alignment with PSO in Error Metrics: The Mean Absolute Error (MAE) and Mean Squared Error (MSE) between IPOA and PSO are lower than those between IPOA and POA. Additionally, the relative error is significantly smaller when comparing IPOA with PSO than with POA, emphasizing IPOA's improved performance.

These error metrics are crucial for understanding the practical implications of choosing one algorithm over another, particularly in scenarios where small differences in power output can have significant consequences.

In essence, the Improved Pelican Optimization Algorithm (IPOA) not only achieves higher average outputs but also demonstrates rapid convergence to optimal performance, making it a superior choice for scenarios where both high efficiency and quick response are critical.

VI. CONCLUSION

The research presented in "Maximizing Solar Panel Efficiency in Partial Shade: The Improved POA Solution for MPPT" effectively addresses a critical challenge in the field of solar photovoltaic systems – optimizing performance under partial shading conditions. The study introduces the Improved Pelican Optimization Algorithm (IPOA), an innovative adaptation of the Pelican Optimization Algorithm (POA), specifically tailored to enhance Maximum Power Point Tracking (MPPT) efficiency in solar PV systems.

Our investigation reveals that the IPOA significantly surpasses the original POA and other prevalent methods like PSO in several key performance metrics. The IPOA not only demonstrates a higher mean power output, indicative of superior average performance, but also achieves this with remarkable consistency and reliability, as evidenced by its notably lower standard deviation compared to its counterparts. This consistency is crucial in real-world applications where variability in power output can significantly impact overall system efficiency.

Furthermore, IPOA's ability to rapidly and accurately identify and track the maximum power point, particularly in the dynamically challenging environment of partial shading, marks a substantial advancement in solar PV optimization. Its enhanced adaptability and precision in response to fluctuating irradiance patterns set a new benchmark in the field.

The study's comprehensive approach, encompassing both simulation and real-world testing, underscores the robustness and practical applicability of IPOA. These findings not only contribute significantly to renewable energy optimization but also pave the way for more efficient, resilient solar energy systems, especially in regions where shading is a frequent concern.

In conclusion, the Improved Pelican Optimization Algorithm emerges as a highly effective and efficient solution for MPPT in photovoltaic systems. Its superior performance, combined with enhanced adaptability and rapid convergence, positions IPOA as a significant advancement in the quest for optimizing solar panel efficiency under the challenging conditions of partial shading.

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