Comparative Study of Genetic Algorithms and Particle Swarm Optimization for Flexible Power Point Tracking in Photovoltaic Systems under Partial Shading

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Abstract. This study conducts a comparative analysis of Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) for Flexible Power Point Tracking (FPPT) in photovoltaic (PV) systems. The GA-based FPPT algorithm exhibits superior performance in power output, tracking accuracy, and convergence speed compared to conventional methods. In contrast, the PSO-based FPPT algorithm is designed to mitigate oscillations around steady-state operating points under partial shading conditions (PSC) by incorporating power limitation control. This allows the FPPT-PSO algorithm to effectively track the global maximum power point (GMPP) without fluctuating around steady-state points. The findings of this comparative analysis highlight the significance of adaptive FPPT algorithms in enhancing system reliability and maximizing power extraction under dynamic environmental conditions. The GA-based approach excels in optimizing power generation metrics, while the PSO-based approach specializes in maintaining stability and precision under challenging operational scenarios such as partial shading. By exploring the strengths and limitations of each algorithm, this study provides valuable in-sights into the selection and implementation of FPPT strategies in PV systems.

1 Introduction

The rising need for electricity has driven the establishment of additional power-generation facilities, notably solar power stations, which are gaining favor due to their myriad advantages [1]. Nonetheless, ensuring grid stability and reliability has become progressively more vital amidst the upsurge in power production [2].

This underscores the need for intensified attention towards active power control methodologies [3]–[6]. To meet these requirements, a flexible power point tracking (FPPT) algorithms have been put forward in scholarly works to enhance the efficacy of solar power installations (SPIs). FPPT algorithms are devised to manage the out-put of solar photovoltaic

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(PV) power systems in accordance with predefined criteria outlined by grid regulations and operational parameters [7]–[9].

FPPT stands as a vital control approach within PV systems, enabling the effective transmission of power to the grid. Nevertheless, under conditions of partial shading (PSC), where certain segments of the PV array are shaded, conventional FPPT algorithms may encounter obstacles, such as being ensnared in local maximum power points (Fig. 1). This scenario can negatively impact both performance and efficiency [10]. The constraints of traditional FPPT techniques mandate the advancement of enhanced control methodologies to tackle these challenges. Moreover, there arises a necessity to adapt the conventional global maximum power point tracking (GMPPT) algorithm to suit the proposed FPPT algorithm and enhance its dynamic responsive-ness following the detection of environmental changes [11].

Several investigations have made significant contributions to regulating PV power and supporting the grid. However, they fail to directly confront the specific hurdles posed by PSC in PV systems [12], [13].

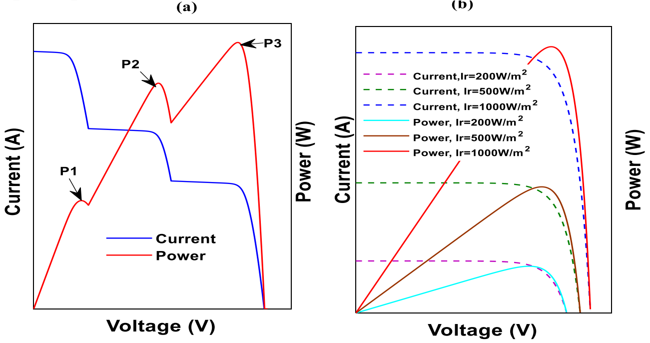

Fig. 1. Challenges of MPPT Techniques in PV systems with PSC.

Publications tackling the issue of PSC in PV systems have suggested inventive remedies to boost power generation and stability amidst adverse environmental circumstances [14]–[17]. However, these publications also highlight some disadvantages, such as fluctuations in power output under PSC.

The significance of this study lies in conducting a comprehensive comparative analysis between Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) algorithms for FPPT under shading conditions [18]. This research aims to shed light on the efficacy of both optimization techniques in maximizing power generation in PV systems amidst shading scenarios. The study rigorously evaluates the performance of GA and PSO algorithms in overcoming challenges related to variable solar irradiance levels and partial shading, with a focus on ensuring maximum power output and seamless grid integration. Through extensive simulations, the comparative study provides valuable insights into the strengths and weaknesses of each algorithm in terms of power generation, tracking accuracy, and convergence speed under shading conditions. The findings offer valuable guidance for practitioners and researchers in selecting the most suitable optimization approach for FPPT in PV systems, thereby contributing to advancements in renewable energy technology and enhancing energy efficiency in solar power generation.

The incorporation of GAs and PSO into MPPT methods has proven to be a robust solution for optimizing PV systems, especially under practical scenarios like PSC. This approach significantly minimizes power fluctuations and boosts total energy production, particularly in PSC [19], [20]. The effectiveness GAs in MPPT was emphasized in [21], showcasing benefits such as rapid tracking, reliability, and robustness in real-time applications.

Collectively, these studies highlight the promise of GAs and PSO in tackling the complexities of MPPT. This results in improved efficiency, reduced power losses, and increased energy production in PV systems, especially under challenging conditions like partial shading. By employing innovative methods and collaborative strategies, GAs are crucial in advancing MPPT techniques, thus playing a significant role in enhancing the efficiency and reliability of renewable energy systems.

The subsequent sections of the article are structured as follows: Section 2 introduces the proposed GA-based FPPT Algorithm and PSO-based FPPT Algorithm. Section 3 details the simulation process, while Section 4 presents and discusses the performance results of the algorithms. Finally, Section 5 concludes the article by summarizing the findings and suggesting future research directions.

2 GA-Based FPPT and PSO-based FPPT

2.1 GA-Based FPPT Algorithm

The creation of an efficient MPPT algorithm is crucial for maximizing energy extraction from PV systems, particularly under challenging conditions such as partial shading. This section introduces our novel GA-based FPPT Algorithm, designed to overcome the difficulties posed by fluctuating irradiance and shading, while also regulating PV power output to comply with grid codes.

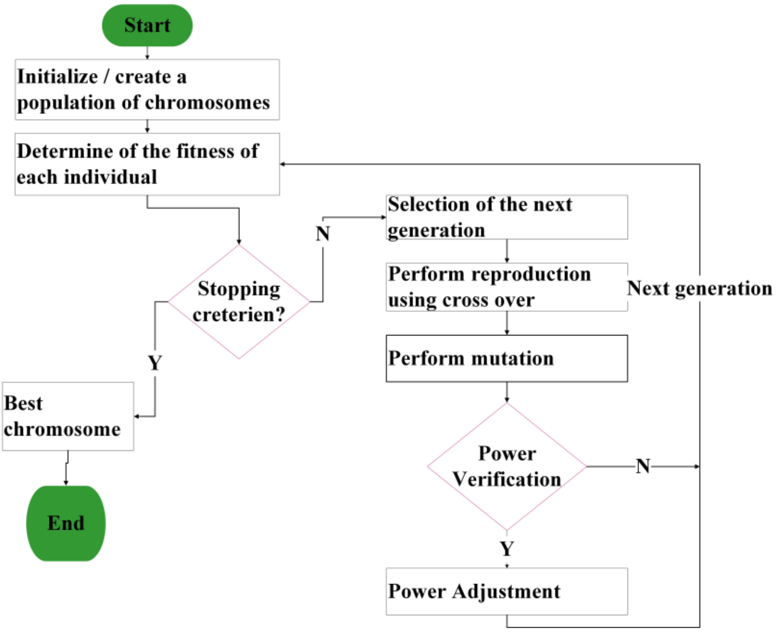

Fig.2. GA-based FPPT algorithm implementation.

The FPPT algorithm utilizes the inherent adaptability of GAs to dynamically adjust the operating point of the PV system in response to changing environmental conditions, ensuring alignment with network requirements. Its main objective is to accurately and efficiently follow the GMPP, guaranteeing optimal energy capture even during partial shading events.

The FPPT Algorithm maintains a population of potential solutions, each representing a unique candidate operating point. Through genetic operations such as selection, crossover, and mutation over successive generations, the algorithm drives the population towards increasingly optimal solutions. The fitness of each solution is evaluated based on its ability to track the GMPP, particularly under partial shading conditions.

To enhance adaptability, the algorithm incorporates an intelligent parameter tuning mechanism that dynamically adjusts its settings in real-time. This feature allows the FPPT Algorithm to quickly respond to sudden changes in shading, ensuring optimal tracking performance without significant delays.

Additionally, the proposed algorithm includes real-time data acquisition and processing capabilities, enabling continuous monitoring of PV system performance. This data-driven approach improves accuracy and responsiveness, allowing the algorithm to effectively mitigate the negative impacts of partial shading and rapidly changing atmospheric conditions.

In this step-by-step guide, we present a strategic approach for implementing a GA for FPPT (Fig. 2). These steps aim to enhance the performance of the PV system, ensuring efficient power output under varying conditions.

- Initialization: A population of potential solutions is generated randomly, with each solution represented as an individual within the GA.
- Fitness Function: The initial step involves defining a fitness function to assess the performance of specific duty cycles, aiming to maximize the solar panels' power output based on input parameters.
- Fitness Evaluation: The fitness function is applied to each individual in the population, calculating their fitness scores based on their ability to maximize the power output of the solar panels.
- Selection: To select parents, a random value R is generated between zero and one. The corresponding segment on the roulette wheel, defined by the accumulated probability range, is then identified.
- Crossover: Selected parameter sets are combined to create new sets, mimicking genetic crossover in nature, with the expectation that these new configurations will show further improvements.
- Mutation: Occasionally, small random changes are applied to certain parameter sets, introducing variability that can potentially lead to better solutions.
- Repetition: The steps of evaluation, selection, crossover, and mutation are repeated over multiple generations of parameter sets.
- Power Adjustment: In a GA-based FPPT system under varying solar radiation levels, if the calculated optimal power output exceeds a predetermined power limit, the generated power is adjusted to align with that limit. Conversely, if the generated power falls below this limit, the standard optimal power is computed using the GA process. This ensures power remains within set boundaries while optimizing solar energy output. During each iteration, solutions are evaluated based on their ability to generate power under different radiation conditions. By integrating these adjustments and evaluations into the GA-based FPPT algorithm, the system dynamically adapts to solar input fluctuations, maximizing energy harvesting while adhering to established power limits. This balanced strategy protects the system from overloading while capturing the maximum available energy from the solar source.

2.2 GA-Based FPPT Algorithm

The primary goal of the FPPT-PSO algorithm is to consistently sustain a steady power output from the PV system at a specified level [22]. It ensures alignment between the PV system and the GMPP, regardless of changes in environmental conditions. The algorithm also adheres to the grid code's reference power and minimizes oscillations around the steady-state operating point.

Step-by-Step Guide to Implement FPPT Based on PSO:

- Initialization: Initialize a population of particles with random positions and velocities within the solution space.
- Define parameters such as the number of particles, cognitive and social coefficients, and the maximum number of iterations.
- Evaluation: Calculate the fitness value for each particle based on the power output of the PV system. Identify the global best (Gbest) position which corresponds to the highest power output observed so far. Identify the personal best (Pbest) position for each particle based on their individual highest power outputs.
- Update Velocities and Positions: Update the velocity of each particle based on its Pbest position, the Gbest position, and the current velocity. Update the position of each particle by adding the updated velocity to the current position.
- Convergence Check: Check if the stopping criteria (such as the maximum number of iterations or a threshold improvement in fitness value) are met. If not, return to the evaluation step.
- Implementation of the Best Solution: Once convergence is achieved, implement the particle with the best position as the solution.
- Adjust the PV system parameters to align with this optimal solution to ensure maximum power point tracking (MPPT).
- Monitoring and Adaptation: Continuously monitor the PV system's performance and environmental conditions. Periodically re-run the FPPT-PSO algorithm to adapt to any changes and maintain optimal performance.

By following these steps, the FPPT-PSO algorithm can effectively maintain a steady power output from the PV system, optimizing performance despite fluctuations and PSC.

Figure 3 illustrates the detailed scheme of the FPPT-PSO algorithm.

Table 1. PV system specifications.

Parameter	Symbol	Value
Number of cells	Ncell	60
Open-circuit voltage	Voc	36.6 V
Short-circuit current	Isc	8.75 A
Voltage at the maximum power point	Vmp	30.436 V
Maximum power point	Pmpp	250.35 W
Current at the maximum power point	Imp	8.22 A
Series resistance	Rs	0.0018 Ω
Diode saturation current	I0	1.5 10-10 A
Shunt resistance	Rsh	8.6278 Ω
Diode ideality factor	A	1.216
Input capacitor	Cin	20 mF
DC-Link voltage	Vdc	400 V
Output capacitor	Cout	5 mF

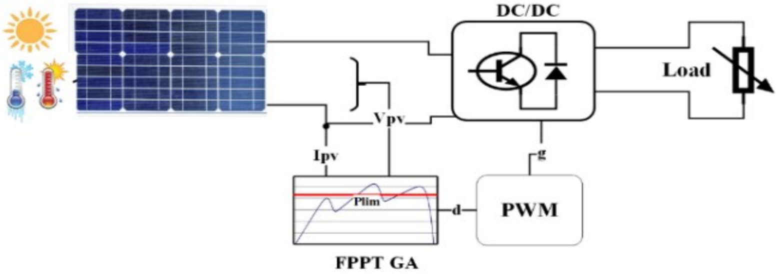

Fig.4. PV system configuration.

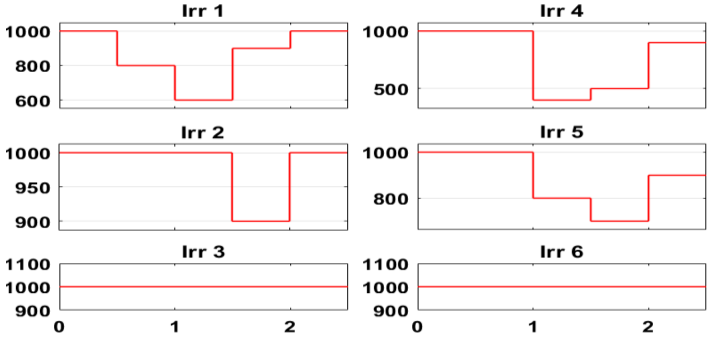

Fig.5. Partial shading scenarios in PV system.

3 Simulation

In this section, we detail the simulation environment employed to assess the performance of both GA-based and PSO-based FPPT algorithms. This thorough evaluation was conducted to confirm the algorithms' effectiveness in optimizing power extraction, adapting to PSC, and adhering to grid code requirements.

In our study, we conducted simulations using MATLAB/Simulink software. This platform provides a flexible and customizable environment for modeling and simulating PV systems under diverse conditions. We incorporated well-known PV module models, environmental data, and shading profiles to realistically replicate real-world scenarios. To assess the performance of both GA-based and PSO-based FPPT algorithms, we used a PV system with the specifications detailed in Table 1.

To thoroughly evaluate the effectiveness of both GA-based and PSO-based FPPT techniques, it is essential to model and program the various key components of the PV system. This involves creating precise representations of the PV array, the FPPT GA controller, the PSO controller, and the DC/DC boost converter. Each of these components is critical in assessing the algorithms' performance and their ability to optimize power extraction under dynamic conditions, such as partial shading.

Lastly, the DC/DC boost converter, which acts as a vital link between the PV array and the load/grid, must be simulated to accurately reflect its switching behavior, control loop, and efficiency characteristics. This converter regulates the power flow and voltage levels in the system, significantly influencing the overall efficiency of power extraction.

These individual components were seamlessly combined into a unified system, as illustrated in Figure 4.

The photovoltaic system consisted of eight solar panels arranged in three series-connected strings. Each panel had a power rating of 250 W, with detailed specifications provided in Table 1. These panels were linked to a power converter to facilitate efficient energy conversion. Voltage and current sensors were strategically positioned throughout the system to supply real-time data for analysis. To ensure consistency in our evaluation, we set the operating conditions of the PV system to demonstrate rapid fluctuations in irradiance, as depicted in Figure 5.

4 Results and Discussion

Our PV system, utilizing the advanced FPPT GA algorithm [18], exhibited outstanding performance, as illustrated in Figure 6. These charts display the system's outputs under different conditions (refer to Fig. 5), highlighting the algorithm's effectiveness in maximizing power generation. A notable feature is the system's consistent ability to produce significant power outputs while adhering to predefined power limits.

A thorough comparison of the GA-based FPPT algorithm with the current PSO-based FPPT highlights its superiority in power extraction, tracking precision, and convergence speed. The most significant achievement of the GA-based FPPT algorithm is its outstanding performance under PSC.

$$E_{ss} = \frac{\int |p_{pv} - p_L|}{\int |p_{pv}|} \times 100$$

The equation below is used to calculate the error in steady-state tracking. Specifically, the integrals within the equation are evaluated over the time interval from t=0.5 s to t=2s, which represents the duration when the algorithms are functioning in a stable state.

An analysis of tracking accuracy, as shown in Table 2, demonstrated that the GA-based FPPT achieved higher precision, consistently operating closer to the MPP. The convergence speed was measured by the time the algorithm took to reach the MPP following dynamic changes. The GA-based FPPT algorithm consistently showed faster convergence times compared to other methods.

The findings revealed that the GA-based FPPT algorithm swiftly recovered from shading events, significantly reducing the impact of PSC on energy yield. Despite its complexity, the algorithm exhibits fast computation times, making it well-suited for real-time applications in changing environments. Overall, the results highlight the robustness and adaptability of the GA-based FPPT algorithm in dynamic conditions.

The algorithm's exceptional performance under PSC scenarios positions it as a highly promising solution for improving energy extraction in real-world PV systems. These results underscore the potential of GA-based FPPT algorithms to significantly advance power point tracking techniques in photovoltaic systems.

These results underscore the substantial benefits of the GA-based FPPT algorithm compared to traditional MPPT techniques, particularly in terms of improved power extraction and tracking accuracy. By integrating FPPT capabilities, the algorithm can dynamically adapt to fluctuating environmental conditions, making it an invaluable tool for maximizing energy yield.

Integrating the GA-based FPPT algorithm can significantly enhance PV system efficiency, resulting in increased energy production and cost savings over the system's lifespan. By reducing power losses due to partial shading, this algorithm can make photovoltaic systems more economically viable and environmentally sustainable.

The comparison between the proposed algorithm and the GA-based FPPT method highlights the importance of adaptive algorithms in contemporary photovoltaic systems. The GA-based FPPT algorithm's proficiency in managing partial shading scenarios demonstrates its potential to surpass traditional methods in real-world applications.

Furthermore, examining the dynamic responses across various scenarios provides insights into the algorithm's adaptability and resilience in addressing different irradiance conditions. Accurate tracking is crucial for maximizing power generation in ideal conditions. The algorithm demonstrates consistent and dependable performance even in scenarios with moderate to low irradiance levels. The minimal steady-state error observed in these situations highlights the algorithm's effectiveness in ensuring a stable power output, which is crucial for optimizing long-term energy yield. Taken together, these findings confirm the FPPT-PSO algorithm's potential to enhance PV system performance under partial shading conditions, underscoring its significance in bolstering grid stability and maximizing energy generation efficiency.

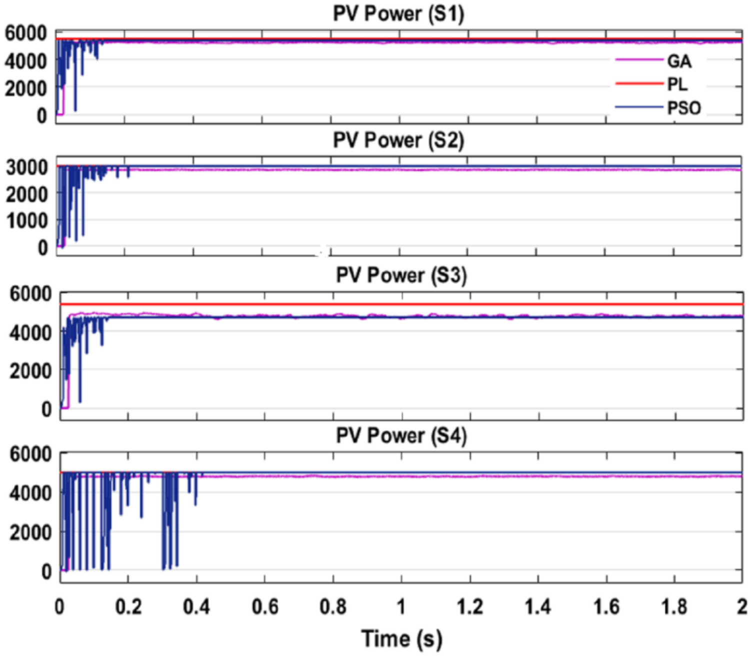

Fig.6. FPPT based GA and PSO under PSC scenarios.

Table 2. Performance of FPPT based GA and PSO.

Parameter under S1 (PL=5500W)	**FPPT-PSO**	**FPPT-GA**
Rise time(s)	2e-03	2.5403 e-04
Overshoot (%)	25	102
Extracted power (W)	5325.57	5179
Eff (%)	99.28	96.55
Parameter under S2 (PL=3000)		
Rise time(s)	2e-03	4.3168e-07
Overshoot	0	79
Extracted power (W)	2960.17	2817.13
E_{ss}(%)	1.35	6.49
Parameter under S3 (PL=5400)		
Rise time(s)	1.2e-02	4.4134e-07
Overshoot	4.63	355.83
Extracted power (W)	4660	4658
Eff (%)	99.97	99.93
Parameter under S4 (PL=5000)		
Rise time(s)	2e-03	4.3728e-07
Overshoot	0	53.42
Extracted power (W)	4953.03	4740.32
E_{ss}(%)	0.95	5.48

5 Conclusion

This article explored the performance of a photovoltaic (PV) system utilizing an advanced Genetic Algorithm (GA)-based Fast Perturb and Observe (FPPT) algorithm. The results demonstrate that the GA-based FPPT algorithm outperforms traditional methods, including the Particle Swarm Optimization (PSO)-based FPPT algorithm, in terms of tracking precision, convergence speed, and robustness under partial shading conditions.

The analyses show that the GA-FPPT algorithm effectively maximizes power generation even under fluctuating irradiance conditions. The algorithm adapts quickly to environmental changes, minimizing steady-state errors and thereby enhancing the long-term energy yield of PV systems.

Integrating this algorithm into PV systems can significantly improve their efficiency by reducing power losses due to partial shading, making these systems more economically viable and environmentally sustainable. The GA-FPPT algorithm stands out for its ability to optimize energy production in challenging conditions, making it a valuable tool for real-time applications in dynamic environments. In conclusion, the GA-FPPT algorithm represents a major advancement in the optimization of PV systems. It offers promising prospects for increasing energy production, reducing operational costs, and supporting a transition to more sustainable and efficient renewable energy sources.

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