Intellectual Journal of Energy Harvesting and Storage
Vol. 3, No. 2, December 2025, pp. 74~79
ISSN: 2963-6272, DOI: 10.11591/ehs.v3i2.pp74-79

Swarm intelligence-based maximum power point tracking algorithms for partial shading in photovoltaic systems

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Article Info

Article history:

Received July 7, 2025
Revised Oct 15, 2025
Accepted Oct 30, 2025

Keywords:

Maximum power point tracking
Partial shading
Particle swarm optimization
Photovoltaic
Swarm intelligence

ABSTRACT

The rapid expansion of photovoltaic (PV) technology has increased the demand for efficient energy conversion, especially under partial shading conditions commonly found in real-world environments. Conventional maximum power point tracking (MPPT) methods, such as perturb and observe (P&O) and incremental conductance (INC), often perform poorly under fast-changing shading, resulting in power oscillations and energy losses. To address these limitations, intelligent optimization techniques, including machine learning and simulation-based methods, have been explored. Among them, swarm intelligence (SI) algorithms, inspired by collective behavior in nature, have demonstrated strong adaptability to dynamic operating conditions. Nevertheless, many existing MPPT approaches still face challenges in achieving fast convergence, global optimal tracking, and stable operation under severe partial shading. This study evaluates SI-based MPPT methods, focusing on particle swarm optimization (PSO), the firefly algorithm (FA), and a hybrid particle swarm–fireworks (PS-FW) approach. Comparative results show that SI-based techniques outperform conventional MPPT methods in terms of tracking accuracy, convergence speed, and stability. These improvements enhance the reliability and efficiency of PV systems, supporting sustainable energy generation and providing guidance for robust PV operation under diverse environmental conditions.

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1. INTRODUCTION

Photovoltaic (PV) systems convert sunlight directly into electricity through semiconductor materials via the PV effect. They are central to global initiatives addressing climate change by providing clean and sustainable energy. However, their efficiency is strongly influenced by environmental factors such as shading, temperature variations, and irradiance changes. Among these, partial shading is particularly problematic, as it alters the power–voltage characteristics of PV modules and reduces overall energy output [1].

Partial shading creates multiple local maximum power points (MPPs) while only one global maximum power point (GMPP) exists. Conventional maximum power point tracking (MPPT) methods, such as perturb and observe (P&O), and incremental conductance (INC), often fail to identify the GMPP under these nonlinear conditions. As a result, PV systems may operate at suboptimal points, leading to energy loss and reduced reliability [2], [3]. This challenge underscores the need for advanced MPPT strategies capable of maintaining efficiency under rapidly changing shading patterns.

To address these limitations, researchers have explored intelligent optimization techniques, including artificial intelligence, and hybrid controllers, which demonstrate faster convergence and improved stability [2], [4]. Swarm intelligence (SI), inspired by collective behaviors in nature such as bird flocking or fish schooling, has emerged as a promising approach. Algorithms such as particle swarm optimization (PSO) and the firefly algorithm (FA) leverage decentralized control and self-organization to adaptively search for global optima. These methods have shown superior performance compared to traditional MPPT techniques, particularly in complex shading scenarios [2], [3].

Despite encouraging results, existing studies often focus on individual SI algorithms or limited test conditions. A systematic comparison of different SI-based MPPT strategies under diverse partial shading scenarios remains underdeveloped. Furthermore, the integration of hybrid swarm approaches, which combine the strengths of multiple algorithms, has not been fully explored in PV applications [3], [4]. This study investigates SI-based MPPT algorithms for PV systems under partial shading. Specifically, it evaluates PSO, the FA, and a hybrid particle swarm–fireworks (PS-FW) method. By analyzing their tracking accuracy, convergence speed, and stability, the research clarifies how SI can enhance MPPT optimization compared to conventional approaches. Experimental and simulation results are integrated to provide a comprehensive assessment [2]–[4].

The findings demonstrate that SI algorithms significantly improve energy extraction efficiency and reliability in PV systems facing partial shading. This work contributes to the advancement of sustainable energy technologies by offering design guidelines for robust MPPT strategies. More broadly, it highlights the potential of bio-inspired computation to optimize renewable energy systems, supporting the transition toward smarter and more resilient solar power generation [3], [4].

2. FUNDAMENTALS OF SWARM INTELLIGENCE

Swarm intelligence (SI) is inspired by the collective behavior of decentralized and self-organizing natural systems. It models biological phenomena such as bird flocking, fish schooling, and insect foraging, where simple local interactions lead to complex global behavior. SI algorithms are effective in finding optimal solutions and adapting to dynamic environments, making them well suited for energy optimization problems. One prominent SI-based method is particle swarm optimization (PSO), which has been widely applied to maximum power point tracking (MPPT) in photovoltaic (PV) systems. PSO uses collective swarm behavior to handle partial shading, irradiance changes, and temperature variations, ensuring reliable power extraction from PV modules [1], [5]. These advantages demonstrate the strong potential of SI algorithms in advancing renewable energy technologies and supporting sustainable energy systems.

2.1. Definition and principles of swarm intelligence

Swarm intelligence (SI) is a computational approach inspired by the collective behavior of social organisms such as birds, fish, and insects. It is based on decentralized and self-organizing systems, where simple local interactions among agents lead to effective problem-solving in complex environments. Key principles of SI include cooperation, local interaction, and adaptability, achieved without centralized control. These characteristics make SI particularly suitable for optimizing maximum power point tracking (MPPT) in photovoltaic (PV) systems, especially under partial shading conditions. Previous studies show that SI-based algorithms, such as particle swarm optimization (PSO), can enhance MPPT efficiency by dynamically adapting to environmental changes. This adaptability is crucial for addressing the nonlinear behavior of PV systems, making SI a relevant and effective framework for energy optimization applications [2], [6].

2.2. Common swarm intelligence algorithms

A number of algorithms based on SI have come forth as potential solutions aimed at optimizing the MPPT within PV systems, specifically when faced with conditions of partial shading. These approaches, which take inspiration from the collective behaviors seen in natural systems, show a capability to adeptly maneuver through intricate search spaces, thus improving the efficiency of energy extraction. Notable among these methods, PSO and FA have illustrated notable capacity in pinpointing global maxima accurately, even when dealing with the non-linear output characteristics of PV systems that are further complicated by environmental changes like temperature and irradiance variations [5]. Considering the ongoing research, conventional techniques such as P&O and INC typically find themselves facing difficulties under variable shading conditions, as they often converge to local optima [3]. Hence, the proficiency of SI algorithms in finding a balance between exploration and exploitation is proven to be pivotal in boosting the energy yield of PV systems under difficult operational circumstances.

2.3. Applications of swarm intelligence in engineering

The incorporation of SI into the field of engineering has significantly changed the approaches utilized for solving problems, particularly when it comes to optimizing complex systems. Methods pulled from natural collective activities, like those seen in groups of birds or fish, have been quite successful in improving the functionality of PV systems across different conditions. In particular, SI offers stronger strategies for MPPT, tackling issues that arise from partial shading—a situation where traditional MPPT techniques, such as P&O, have difficulty locating the global MPP, given the existence of several local maxima [3]. Through the use of algorithms that draw inspiration from SI, engineering solutions are capable of adapting and progressing towards optimal performance paths, thereby boosting operational efficiencies. This ability to adapt not only increases the energy output of PV systems but also mitigates the intrinsic weaknesses associated with traditional tracking methods [7], thereby emphasizing the significant impact of SI in engineering contexts.

2.4. Advantages of swarm intelligence in optimization problems

The utilization of SI techniques in optimization challenges presents particular advantages that considerably elevate system performance and adaptability. By emulating natural phenomena observable in social organisms, like the group behavior of avian flocks or aquatic schools, these algorithms navigate intricate solution landscapes with considerable efficacy, demonstrating sturdy convergence traits. Such robustness is especially pronounced in MPPT contexts for PV systems, where SI methodologies, namely PSO and FA, have shown superior performance compared to conventional methods. For example, Sagonda and Folly [5] highlights how these algorithms sustain high efficiency and swift convergence even amidst fluctuating environmental circumstances, such as instances of partial shading. Furthermore, the comparative investigation articulated in [8] emphasizes the diminished computational load and improved tracking abilities afforded by swarm-based techniques, thereby reinforcing their dominance in dynamic environments. Consequently, SI not only simplifies problem-solving frameworks but also bolsters the dependability of renewable energy systems.

3. MAXIMUM POWER POINT TRACKING TECHNIQUES FOR PHOTOVOLTAIC SYSTEMS

Effective MPPT is crucial for PV systems, particularly under partial shading conditions where conventional methods often struggle. Traditional algorithms such as perturb and observe (P&O) and incremental conductance (INC) have difficulty identifying the global maximum power point (GMPP) due to multiple power peaks caused by shading effects [3]. Recent studies emphasize the use of swarm intelligence (SI)–based algorithms, which offer greater robustness and adaptability under varying shading conditions. In particular, differential evolution (DE) optimization has demonstrated better performance than traditional MPPT techniques by consistently delivering higher output power under non-uniform conditions [7]. These findings highlight the need for advanced MPPT methods that can maximize energy extraction, improve system efficiency, and support cost-effective renewable energy solutions. Consequently, the development of intelligent MPPT algorithms is essential for enhancing PV system performance in challenging environments.

3.1. Traditional maximum power point tracking methods and their limitations

In the efforts to enhance PV systems, the conventional MPPT methodologies encounter notable constraints that obstruct their efficacy, particularly amid fluctuating environmental conditions. These methods, typically relying on perturbation-based approaches like INC and P&O, frequently find it challenging to swiftly recognize the GMPP, especially when faced with partial shading or quick variations in solar irradiance, which may result in reduced effectiveness in energy extraction. A fundamental limitation resides in their inability to appropriately differentiate between local and global maxima, leading to less than optimal performance and energy generation [2]. In addition, their high sensitivity to noise and environmental changes could generate considerable oscillatory behavior and extend settling durations during tracking. As a result, scholars have started to investigate more advanced methodologies, such as hybrid MPPT techniques that meld the advantages of traditional strategies with artificial intelligence, thereby attaining improved convergence and efficiency, which subsequently enhances the performance of solar energy systems overall [4].

3.2. Overview of swarm intelligence-based maximum power point tracking algorithms

MPPT algorithms based on SI signifies a novel method of enhancing the efficiency of PV systems, particularly when faced with diverse environmental changes. These algorithms draw inspiration from natural swarming behaviors, like those seen in avian species and aquatic creatures, utilizing collective intelligence to adeptly find the GMPP amid numerous local peaks, which are frequently present during conditions of partial shading or variable irradiance and temperature. The adjusted PSO approach, as depicted in the analytical study, shows notable enhancements in convergence speed and response time in relation to conventional methods [1]. Furthermore, the incorporation of adaptive mechanisms within these SI frameworks improves their resilience, allowing them to promptly modify tracking strategies in real time. Such progress not only facilitates more reliable energy capture but also highlights the capability of SI techniques to tackle intricate issues in the realm of renewable energy optimization [2].

3.3. Comparative analysis of maximum power point tracking techniques

The performance of MPPT techniques shows considerable variation in scenarios involving partial shading, which makes it essential to conduct a comparative study of these approaches. Conventional algorithms, including P&O and INC, tend to perform well under uniform conditions; however, they struggle when faced with the intricacies introduced by partial shading, which can result in the presence of multiple peaks that lead to less than optimal performance [3]. On the other hand, meta-heuristic algorithms, such as the enhanced grey wolf optimizer (EGWO), have been shown to possess far better capabilities in effectively navigating the complex terrain associated with global maxima, thereby overcoming the shortcomings of traditional methods [9]. These advanced algorithms can dynamically investigate potential power peaks, significantly reducing the likelihood of being led astray by local maxima—an important drawback associated with more conventional strategies. This comparison highlights the pressing need for creative approaches to bolster the reliability and effectiveness of MPPT techniques, especially in environments characterized by variable shading, thereby propelling advancements in the domain of PV energy generation.

3.4. Role of swarm intelligence in enhancing maximum power point tracking efficiency

Recent developments regarding the enhancement of MPPT efficiency have brought to light the crucial role that SI plays within PV systems, particularly under circumstances of partial shading. SI methodologies, which draw inspiration from natural behavioral patterns identifiable in biological entities, provide resilient resolutions for optimizing energy extraction from PV modules. Among these methodologies are PSO and grey wolf optimization, both of which demonstrate proficiency in maneuvering through intricate, multi-peak power curves that arise due to fluctuating environmental influences. Importantly, Saeed *et al.* [10] points out the efficacy of the enhanced opposition-based PSO in obtaining improved convergence rates alongside diminished complexity in contrast to traditional methodologies. Moreover, Al Garni *et al.* [11] highlights that amalgamated strategies that merge SI with conventional techniques can foster better overall performance in ever-changing conditions, thereby confirming that these methodologies outshine standard algorithms in terms of both tracking efficiency and precision. In summary, the incorporation of SI into MPPT methodologies not only alleviates the adverse effects of shading but also assures optimal power production, positioning this strategy as a fundamental element in the future design of PV systems. Figure 1 illustrates the Swarm intelligence algorithms-based MPPT for partial shading in photovoltaic systems.

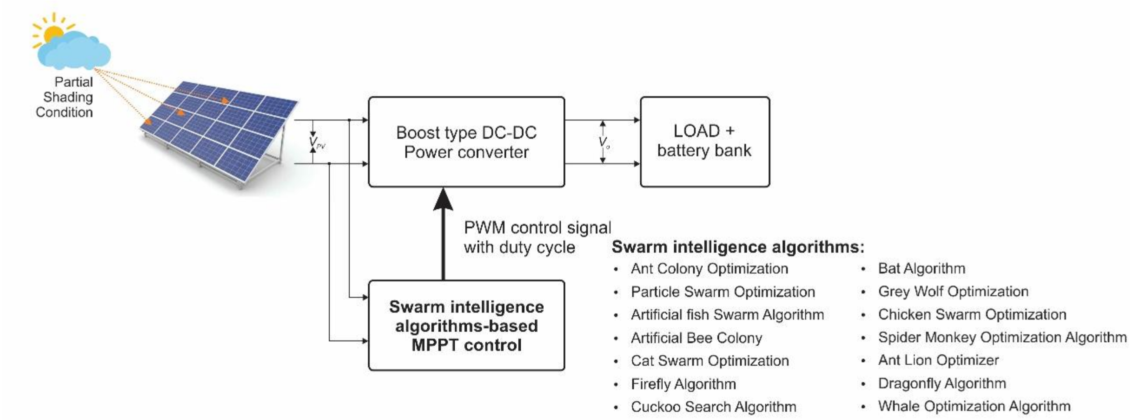

Figure 1. Swarm intelligence algorithms-based MPPT for partial shading in photovoltaic systems

4. IMPACT OF PARTIAL SHADING ON PHOTOVOLTAIC PERFORMANCE

The performance aspects of PV systems encounter notable diminishment owing to the phenomenon known as partial shading, which induces non-uniform illumination conditions across the solar cells. When such partial shading arises, it engenders significant fluctuations in the output power, as disparate segments of the panel might experience differing levels of irradiance. This disparity can instigate a sub-optimal operational state for the PV system, leading to pronounced energy loss. Research has indicated that the incorporation of sophisticated MPPT algorithms is vital for alleviating these adverse effects. For example, the utilization of machine learning-based methodologies has been observed to yield a significant enhancement in power efficiency and stability amid varying environmental conditions [12]. Furthermore, dependable simulation frameworks have effectively demonstrated the necessity of precise modeling of PV system responses to these shading scenarios, verifying their ability to mirror the complexities of real-world performance [13]. Thus, comprehending and addressing the repercussions of partial shading remains crucial for the enhancement of the overall effectiveness of PV systems.

4.1. Mechanisms of partial shading in photovoltaic arrays

Fluctuations in solar insolation resulting from partial shading have a notable effect on the energy output levels of PV arrays, causing distinct nonlinear behavior in their operational performance. Such shading circumstances may emerge from multiple sources including proximal obstructions, environmental variations, or intentional design choices, leading to specific zones within the PV array that receive diminished solar radiation as compared to others. As indicated in [14], the occurrence of partial shading produces intricate current-voltage (I–V) traits, thereby requiring advanced MPPT algorithms to guarantee maximal energy retrieval. Additionally, the demand for precise and swift responsiveness in these scenarios has spurred the progression of diverse MPPT strategies aimed at alleviating the shading repercussions. As noted in [15], a considerable volume of studies has concentrated on soft computing-oriented MPPT methodologies that are adapted for situations of non-uniform irradiance, highlighting a prominent avenue for further investigation and creative endeavors in this essential domain of PV system effectiveness.

4.2. Effects of partial shading on energy output

The occurrence of partial shading produces meaningful hindrances to the energy production capabilities of PV systems, thereby creating notable difficulties for efficient power generation. Given the variations in solar irradiance prompted by clouds or nearby edifices, the resulting non-linear output behavior complicates the forecasting of energy yield, which in turn induces an efficiency decline. This intricacy increasingly necessitates the adoption of sophisticated MPPT methods to guarantee optimal operational effectiveness. Conventional approaches frequently face challenges in locating the GMPP amidst the several peaks that arise under conditions of partial shading, as evidenced by the shortcomings of P&O and INC algorithms in such scenarios [3], [5]. Conversely, SI-based algorithms, like PSO and FA, exhibit enhanced reliability and efficiency, adeptly maneuvering through these complex situations while seeking to maximize energy yield. Therefore, it is of paramount importance to tackle the detrimental impacts of partial shading to elevate the overall feasibility and efficacy of PV systems within practical applications.

4.3. Strategies for mitigating partial shading effects

Partial shading notably detracts from the operational efficacy of PV systems, which necessitates the development of innovative strategies for addressing this issue. A prominent approach is the employment of advanced MPPT algorithms which are tailored to tackle the nonlinear power-voltage characteristics that emerge under different shading conditions. Conventional MPPT methods frequently encounter difficulties in pinpointing the GMPP when multiple local maxima exist, a situation that is often encountered in scenarios involving partial shading [3]. Recent progress in the field has seen the application of bio-inspired algorithms, such as the roach infestation optimization (RIO) algorithm, which showcases improved tracking performance and accuracy, thereby outpacing traditional approaches like P&O, especially in environments characterized by dynamic shading patterns [14]. The incorporation of such intelligent algorithms holds the potential to markedly augment the resilience of PV systems in response to shading fluctuations, consequently optimizing energy output. These strategies are not only progressive advancements in the domain of MPPT but also serve the broader objective of fostering enhanced utilization of renewable energy across various climatic conditions.

4.4. Case studies of partial shading in real-world photovoltaic systems

Partial shading imposes notable difficulties on PV systems, causing a significant reduction in both energy production and efficiency. Empirical case studies have clearly demonstrated the significant effects of shading on performance, indicating that even minimal obstructions, such as tree branches or adjacent buildings, can lead to considerable losses resulting from the non-uniformity of irradiance conditions. Such shading phenomena can give rise to multiple local MPPs, thereby complicating the process of tracking the GMPP which is crucial for achieving optimal performance. It has been noted that conventional MPPT methods often struggle under such circumstances, which leads to the need for further investigation into advanced algorithms. The incorporation of SI-based MPPT algorithms has appeared as a fortuitous remedy, as they are adept at maneuvering through the complex terrain of changing MPPs. By employing methodologies such as PSO and adaptive neural-fuzzy inference systems, researchers have exhibited enhanced tracking efficiency, highlighting the significance of adaptive strategies in alleviating the negative repercussions of partial shading [2], [16].

5. CONCLUSION

The results of this study highlight the importance of improving PV system efficiency, particularly under partial shading conditions. Swarm intelligence (SI) has proven to be an effective approach for enhancing power extraction in such complex environments. Comparative results show that SI-based MPPT methods, especially particle swarm optimization (PSO) and the firefly algorithm (FA), significantly outperform conventional techniques such as perturb and observe (P&O) and incremental conductance (INC) in tracking accuracy and reliability. These findings are consistent with previous studies reporting superior performance of evolutionary optimization methods under partial shading. The hybrid particle swarm–fireworks (PS-FW) algorithm further improves MPPT performance by combining the strengths of multiple SI techniques, providing robust and stable tracking under fluctuating shading conditions. Integrating SI-based MPPT methods can therefore increase energy yield and operational reliability of PV systems across diverse environments. Future research should focus on refining hybrid algorithms such as PS-FW and integrating dynamic system models with conventional MPPT approaches to enhance adaptability. Bridging theoretical developments with practical implementation will accelerate the adoption of advanced MPPT techniques and contribute to more efficient and sustainable renewable energy systems.

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