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MPPT CONTROL ALGORITHM BASED ON OPTIMIZATION OF SOLAR SYSTEM UNDER PARTIAL SHADING CONDITION (PSC)

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Abstrak

Sistem fotovoltaik memiliki sifat intermiten karena bergantung pada kondisi lingkungan yang dinamis. Oleh karena itu, metode MPPT dikembangkan untuk melacak daya maksimum sehingga dalam kondisi lingkungan yang bervariasi sehingga sistem fotovoltaik dapat memaksimalkan produksinya. Metode tersebut adalah proses identifikasi titik daya maksimum melalui pelacakan yang dapat dilakukan dengan berbagai algoritma yang dikenal sebagai metode MPPT. MPPT menghadapi tantangan selama kondisi lingkungan yang dinamis, seperti ketika terjadi *Partial Shading Condition* (PSC) di mana panel surya menerima iradiasi yang tidak merata yang dapat menyebabkan kerugian daya dan memengaruhi kinerja panel surya. Selama kondisi PSC, tidak semua algoritma MPPT memiliki kemampuan untuk menemukan titik maksimum yang akurat sehingga algoritma berbasis optimasi digunakan untuk melacak titik daya maksimum secara akurat dan dalam waktu singkat. Makalah ini memberikan tinjauan komprehensif tentang beberapa algoritma MPPT berbasis optimasi dengan menyoroti kemampuan setiap metode dalam hal kecepatan, stabilitas, dan efisiensi di bawah kondisi PSC.

Kata kunci: MPPT, PSC, Fotovoltaik, Optimisasi

Abstract

The photovoltaic system has an intermittent nature because it depends on dynamic environmental conditions, therefore a method is developed to track the maximum power so that in varying environmental conditions photovoltaic system can maximize its production. The method is the process of identifying the maximum power point through tracking which can be done with various algorithms known as the MPPT method. MPPT faces challenges during dynamic environmental conditions such as when Partial Shading Condition (PSC) occurs where solar panels receive uneven irradiation which can cause power losses and affect the performance of solar panels. During PSC conditions, not all MPPT algorithms have the ability to find the accurate maximum point so that optimization-based algorithms are used to track the maximum power point accurately and in a short time. This paper provides a comprehensive review of several optimization-based MPPT algorithms by highlighting the capabilities of each method in terms of speed, stability and efficiency under PSC conditions.

Keywords: MPPT, PSC, Photovoltaic, Optimization

1. Introduction

The utilization of solar energy potential as a renewable energy source that is abundant and environmentally friendly to generate electricity is increasingly optimal as seen from the increase in the use of photovoltaic (PV) systems to reach 500 GW worldwide [1]. This abundant energy potential is accompanied by challenges that must be faced in the application of photovoltaic systems, namely the output power of solar panels which is influenced by several factors such as temperature, solar irradiation, shading and loading [2]. Solar power plants have the disadvantage of intermittent nature where there is instability in electricity production caused by dependence on solar irradiation. Instability between production and demand will cause the system frequency to be unstable, affecting system stability and reliability [3].

The implementation of maximum power point tracking (MPPT) methods aims to ensure that the system consistently achieves maximum output power under dynamic and varying environmental conditions [4]. Solar panel systems have non-linear characteristics shown through the relationship between current and voltage and the relationship between power and voltage, from this relationship it is found that there is a point where the system produces maximum power [5]. The maximum power point will always change depending on the intensity of sunlight, temperature, environmental conditions and will have an impact on the power generated. The generated power will fluctuate following these intermittent factors and the maximum power generated is expected to be in accordance with the initial design when the intermittent factor is minimally accepted by the system [6]. The process of obtaining maximum power under various influences of intermittent nature is carried out by a combination of a power converter with an MPPT algorithm [5] [7].

MPPT methods can be categorized in many features such as efficiency, dynamic response, convergent speed, sensor requirements, cost, complexity [8]. The purpose of these MPPT methods is to ensure that any change in output power will always be zero to the voltage which can be seen easily through the power to voltage relationship curve. In an effort to get the zero value, the current and voltage measurements of the output panel are carried out and then match the impedance of the source and load. Furthermore, by adjusting the working cycle of the converter with MPP impedance will be tracked [9].

Another factor that causes energy production losses is partial shading conditions (PSC). Partial Shading Condition (PSC) is a situation when solar panels receive uneven irradiation. Solar panels working under PSC conditions can experience the impact of hotspots where the panel receives excessive heat compared to other areas which can cause damage to solar panels and the system[10]. Under PSC conditions the system will have multiple local maximum points in contrast to full sun conditions which only have a single maximum point. The complexity increases when there are many peaks in the P-V characteristic curve so a more accurate control system is needed to distinguish between local and global maximum power points in order to ensure maximum power [11]. Partial Shading Condition becomes a more complex condition for solar panels that can cause a decrease in power efficiency [12][13].

There are various MPPT methods that can be classified based on their tracking methods. Each method has different tracking adaptive capabilities when faced with conditions that are influenced by strong intemiteness. Based on its tracking ability during PSC conditions, the MPPT method can be classified into 3, namely the classic MPPT method, artificial intelligence-based MPPT and optimization-based MPPT [14]. Classical MPPT methods that have been widely developed such as Perturb and Observe (P&O) [15], [16], [17], Incremental Inductance (INC) [18], Open Circuit Voltage [19], Short Circuit Voltage, Hills Climbing[16], [20], [21]. The conventional method has an algorithm architecture whose hardware requirements are relatively cheap and simple. The conventional MPPT method focuses on maximum point tracking speed and has good tracking accuracy under shadowless irradiation conditions. The limitations of the conventional MPPT method are poor adaptive capability, high steady-state error, slow transient response, power oscillation at MPP, inability to find GMPP because it is trapped at LMPP during PSC [22].

Artificial intelligence-based MPPT method is developed to deal with dynamic environmental conditions as one of the intermittent properties faced by the system. Artificial intelligence-based MPPT methods have high adaptive capabilities due to complex data processing and training and are accompanied by a good level of efficiency. Artificial intelligence-based MPPT methods also come with several challenges in their application such as significant control circuit complexity and large data processing requirements for the prior training process of the system [23]. Artificial intelligence-based MPPT methods that have been developed to overcome the influence of strong intermittent properties are Fuzzy Logic Controller (FLC) [24], Artificial Neural Network (ANN) [25], Sliding Mode Control, Fibonacci Series-Based MPPT, Gauss Newton Technique, Genetic Algorithms [26].

These optimization-based MPPT methods are grouped based on metaheuristic optimization designed with the aim of being able to identify the MPP under dynamic environmental conditions such as PSC, temperature. The implementation of these methods has a lower cost than artificial intelligence-based methods because they tend to require simpler microcontrollers. Compared to classical methods, Optimization-based methods require fewer temperature and voltage sensors [17], [27]. Optimization-based MPPT methods that have been widely developed are Grey Wolf Optimization (GWO), Ant Colony Optimization (ACO), Artificial Bee Colony (ABC), Cuckoo Search and Particle Swarm Optimization (PSO). This literature review aims to explore the application of optimization-based MPPT methods under partial shading conditions (PSC). The novelty of this research lies in its comprehensive and integrative analysis of metaheuristic MPPT algorithms in parallel with specific converter topologies, a perspective not widely emphasized in previous studies. By establishing a systematic framework that links algorithmic characteristics with converter behavior, this study provides insights into real-time tracking accuracy, reduction of power oscillation, and enhancement of adaptive performance under PSC. Moreover, it contributes to the field by offering practical implementation guidelines to improve cost-effectiveness and efficiency of solar PV systems, especially in environments subject to high intermittency. This approach is expected to promote the development of robust and scalable solar energy solutions tailored to dynamic operating conditions.

2. Method

This research employs a literature review method to collect and analyze various studies relevant to optimization-based MPPT methods in addressing PSC.

This approach aims to identify, assess, and synthesize previous research findings published in scientific journals and conferences related to optimization-based MPPT methods. Various studies used in this review are obtained through indexers or search engines such as Google Scholar, ResearchGate, Science Direct, Elsevier, and IEEE Xplore. The literature review method is chosen for its ability to provide a comprehensive overview of the technological advancements implemented and the potential innovations for the future. The schematic of the study conducted is presented in Figure 1

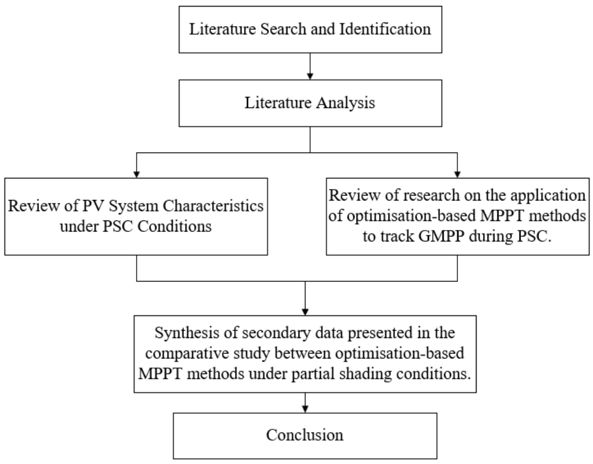

Figure 1. Study Schematic

2.1. Literature Identification

This study employs a literature review approach to analyze and compile findings from various journals and scientific articles related to optimization-based MPPT methods for tracking MPP under Partial Shading Conditions (PSC). The literature review method is chosen as it enables researchers to gather, review, and analyze secondary data from a wide array of scientific sources relevant to the topic. The literature review process encompasses several stages, including the search, selection, and evaluation of previous research results. Initially, an extensive search is conducted to identify pertinent studies and articles that address the optimization-based MPPT methods during PSC. This is followed by a meticulous selection process to ensure the inclusion of high-quality and relevant studies. Finally, the evaluation stage involves a critical assessment of the gathered literature to extract valuable insights and synthesize them into a coherent comparative study. The outcomes of this literature review present the proposed performance of each optimization-based MPPT method in tracking GMPP during PSC, providing a comprehensive understanding of their effectiveness and potential applications

2.2. Literature Analysis

This study examines two main aspects related to Photovoltaic (PV) systems under Partial Shading Conditions (PSC). The first aspect is a review of PV system characteristics during partial shading conditions. This analysis includes an in-depth understanding of how partial shading affects the performance of PV modules, including efficiency reduction, power loss, and the impact of uneven light distribution on solar panels. The second aspect is a review of research on the application of optimization-based MPPT methods to identify GMPP during PSC. Optimization-based MPPT methods are reviewed from various approaches developed in the scientific literature, focusing on the effectiveness and performance of each method in tracking GMPP under partial shading conditions. The results of this literature analysis provide comprehensive insights into the challenges and potential solutions for improving PV system performance using optimization-based MPPT methods during PSC.

2.3. Literature Synthesis

This study conducts a synthesis of literature involving the collection and analysis of secondary data from various scientific sources relevant to optimization-based MPPT methods under partial shading conditions. The purpose of this literature synthesis is to unify various findings and previous research results, and to compile a comprehensive comparative study. This comparative study evaluates the performance of each optimization-based MPPT method in tracking GMPP under partial shading conditions. By integrating various studies, this literature synthesis provides a broader and deeper understanding of the effectiveness, advantages, and limitations of each optimized method. The results of this literature synthesis are expected to provide guidance for researchers and practitioners in selecting the most suitable MPPT method to enhance the performance of Photovoltaic systems under partial shading conditions

3. Results and Discussion

3.1. PV Characteristic Under Partial Shading Condition (PSC)

Solar cells typically exhibit low voltage, current, and output power, limiting their ability to function effectively as standalone units in practical applications. In an effort to get a larger capacity, the solar cells are made into a series circuit and a solar module is formed. Solar cells are commonly represented by single diode models due to their balance of accuracy and simplicity. The equivalent circuit of a solar cell consists of series and parallel resistance is presented in Figure 2 [28]. Solar module composed of multiple solar cell is presented in Fig 3

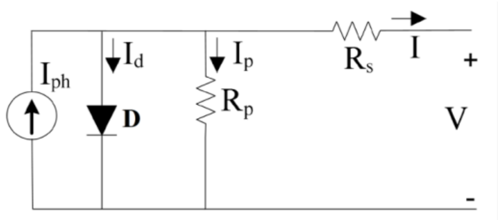

Figure 2. Equivalent circuit of a solar cell

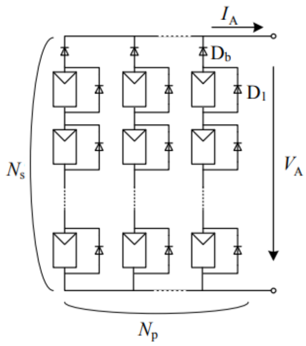

Figure 3. Solar Module Composed of Multiple Solar Cells

The solar module is comprised of PV cells arranged in series and parallel connections. The shaded panels caused by PSC will detect as a load and leading to the formation of hotspot heating, which can potentially damage the entire PV panel. To mitigate this issue, PV panels are typically connected in parallel with bypass diodes [29]. Three PV cells in series are given different scenarios of shadows as shown in Figure 4. From these scenarios, the relationship between power and voltage is different. In the famous solar module, perfect sunlight will only have one peak power. When exposed to shadows in scenarios 2 and 3, several peak power points are produced but there is only 1 actual peak power, namely GMPP and other peak points are LMPP. The curve is shown in Figure. 5 [30].

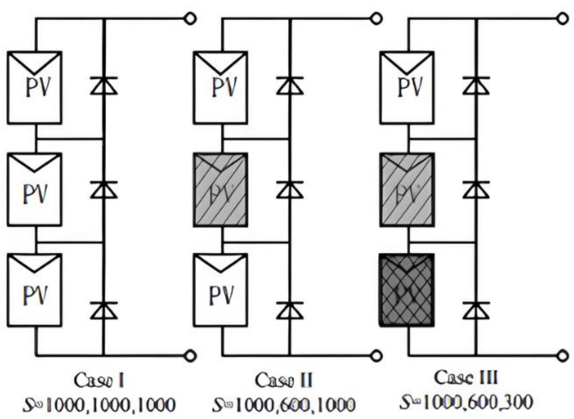

Figure 4. PV Cells With Different Shadows

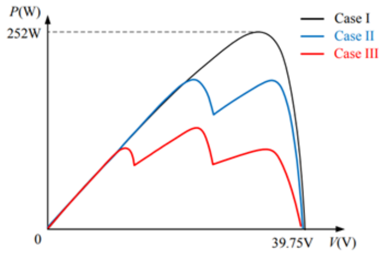

Figure 5. P-V Curve Under 3 Scenario of Shading

3.2. Particle Swarm Optimization (PSO)

The Particle Swarm Optimization (PSO) method is the most researched method based on literature collection from various sources. This method adopts the behavior of flocks of birds or fish that spend most of their lives in groups. The PSO topology visualizes birds or fish as particles, some of these particles gather and form a kind of flock that will travel around the sky which is analogous to a random search space. The algorithm starts and during the process of traveling around in the search space, the flock of particles will continuously update the speed of traveling and try to get the optimal position during the iterative traveling process. During this iterative traveling process, each particle has its own value derived from the objective function, the value is the speed of each to determine the direction and distance between particle positions so that the best position is obtained. The particle will calculate the speed of the next proposal based on the best position that has been successfully determined by the particle itself (Pbest) and then used as a local solution or the best individual. The best position in the herd (Gbest) is used as a global solution. Both Pbest and Gbest values will continue to be updated iteratively as the velocity and position of each particle is updated so that it eventually stabilizes at the global extreme point [12].

In [29] the PSO method is effectively to identify the GMPP well compared to the conventional P&O method during PSC. PSO is not trapped by LMPP and identify exactly to GMPP. However, when the P-V characteristic curve has 2 peak points, PSO is not able to track GMPP accurately. In [31] the PSO algorithm is improved by combining with the extension of voltage window search method, P-V curve scanning and combination with P&O method so as to get the result when the solar irradiation changes rapidly and gradually the algorithm has dynamic performance in finding GMPP so as to save time and the algorithm will not restart unless the accumulated displacement of the operating point is large enough. In [32] the PSO algorithm on 3 different PSC schemes is tested by modifying the duty ratio resulting in effectively able to identify the MPP and produce maximum output power. In Table 1 presents several studies using the Particle Swarm Optimization method.

Table 1. Particle Swarm Optimization Method

MPPT method	MPPT time (s)	Power oscillation	Efficiency (%)	Findings
proposed novel PSO-based MPPT [31]	0.07	Lower than conventional PSO method		The improvement of this method is to enlarge the search window, then add a P-V curve scan and then the GMPP is found. To prevent algorithm restarts and reoptimizes it is combined with P&O.
PSO method using boost converter [33]	0.023			PSO algorithm in combination with boost converter
Modified PSO [12]			98%	The MPSO method was compared with ANN and it was found that MPSO has better efficiency.
PSO using DC-DC converter [29]	0.05	0		In this study, it is highlighted that the combination of PSO and DC converter is able to provide more optimal results compared to P&O.
PSO with parameter variation of duty ratio [32]				The varied duty ratio provides a better optimization effect so that setting the duty ratio according to system conditions is one of the keys to getting optimal results.
Proposed PSO [34]	0.0125		96.96%	The comparative analysis of MPPT performance is conducted by evaluating three parameters: tracking time, tracking error, and efficiency.
Variable Coefficien PSO (VCPSO) [35]	0.34		99.87%	Modifying variable coefficients (w and c) on off grid PV systems

3.3. Cuckoo Search Algorithm (CSA)

The Cuckoo Search Algorithm (CSA), inspired by the parasitism behavior of cuckoo parents, optimizes solutions by mimicking their reproductive strategy. Cuckoo birds lay eggs in the host bird's nest, which resemble the host bird's eggs to avoid detection. If undetected, the cuckoo chicks will hatch early, drive away the host's eggs and monopolize the host's food. This biological strategy improves the efficiency of CSA in exploring the search space, preventing the pitfalls of local optima

The CSA method is similar to the PSO method in that it uses particles but is influenced by the Levy Flights law. Levy Flights is a random walk mechanism, further improving the performance of CSA by ensuring comprehensive coverage of the search space, based on current position and transition probabilities. Based on the simulation performed the CSA takes a longer time to track the GMPP during PSC [36]. The simulation performed in [37], using CSA combined with SPEIC converter shows that from the two PSC schemes performed. In [38] CSA is combined with Super-Twisting Sliding Mode Controller (STSMC). The proposed CSA-STSMC MPPT algorithm has advantages against uncertainty and modelling errors. In Table 2 presents several studies using the Cuckoo Search Algorithm method.

Table 2. Cuckoo Search Algorithm Method

MPPT method	MPPT time (s)	Power oscillation	Efficiency (%)	Findings
CSA MPPT [42]	0.001-0.0025	0.000008%		Only 2 parameters need to be set, making implementation easier.
CSA method combine with Integral Super-Twisting Sliding Mode Controller (STSMC) [38]	0.55	Low and tends to be very low	99.98%	Set 2 parameters for control
Improved CSA [43]	< 0.5 s	0	99.97	The intended improvement is to pull the worst particle with a value close to the global best. Using 3 control parameters.
CSA MPPT combined with the SEPIC converter [37]	0.65	0		In this study, it is highlighted that the combination of CSA and SPEIC converter can provide more optimal results.
CSA [36]	1.2			CSA compared to ANN, ANN is capable to track GMPP faster than CSA
Distributive CSA [44]	< 0,626		99.96	The concept of DSCA is to generate insufficient initial particles and successively increasing values by testing several PSC scenarios.

3.4. Artificial Bee Colony (ABC)

Artificial Bee Colony (ABC) adopts bee swarm behavior to solve multidimensional problems such as optimization. The bee swarm adopted in this ABC method is grouped into three, namely labor bees, spectator bees and scout bees. Labor bees have the task of exploiting food sources. Viewer bees as decision makers to choose food sources. Reconnaissance bees track food sources randomly. These three groups of bees work together to get the optimal solution in a faster duration [39].

The simulation of [40] using the stabilized ABC algorithm under PSC conditions shows that the ABC algorithm able to trace the GMPP faster and effectively without power oscillation at steady state. In [41], it is explained that during PSC, ABC is able to track a larger GMPP power of 74W compared to the PSO method which tracks 72W under the same conditions. This shows that the ABC algorithm is more accurate than the PSO algorithm. The ABC algorithm also has an accuracy that is independent of the initial settings, which only requires information about the number of cells connected in series, while the accuracy of the PSO algorithm is influenced by the initial parameter selection. In Table 3 presents several studies using the Artificial Bee Colony method.

3.5. Ant Colony Optimization (ACO)

The Ant Colony Optimization (ACO) algorithm adopts the attitude of a population of ants to identify the best path to seek food. These ants move randomly to scour the area and then leave a trail of chemical pheromones. These trails will be utilized by other ants as signposts to take the shortest path to the food source [47].

In [48] the ACO algorithm is extended with New Pheromone Update (NPU) to track the GMPP during PSC. This ACO-NPU method has slightly different development steps from the conventional ACO method. The research also compared the ACO-NPU algorithm with the P&O, ANN, FLC, ANFIS algorithms and obtained the results that using ACO-NPU has the best performance in terms of tracking time, accuracy, stability, and robustness, has 0 oscillations during steady state conditions. In Table 4 presents several studies using the Ant Colony Optimization method.

Table 3. Artificial Bee Colony Method

MPPT method	MPPT time (s)	Power oscillation	Efficiency (%)	Findings
Proposed ABC [41]	0.2	0		The ABC method was compared with PSO and obtained more optimal results using ABC.
ABC [45]	0.07	0	99.57	Better performance of ABC method with the use of boost converter
ABC [46]	0.16	0	98.41	In this study, it is highlighted that the combination of ABC and DC converter

Table 4. Ant Colony Optimization Method

MPPT method	MPPT time (s)	Power oscillation	Efficiency (%)	Findings
ACO with New Pheromone Updating strategy [48]	1.2	0	98	ACO_NPU has faster convergence speed and better efficiency than ANN, FLC, ANFIS, P&O, GA algorithms.
Proposed ACO [52]	1.3	0	99.99	Modify the ant colony with a fixed population size to expand the solution room at the earliest food search stage, after approaching the global optimum, the population will be depleted.
ACO [47]	0.4			The improved control scheme is highlighted in this study and makes ACO more optimized.

Table 5. Grey Wolf Optimization Method

MPPT method	MPPT time (s)	Power oscillation	Efficiency (%)	Findings
GWO [12]	0.2	0	98.41	Simulated with several PSC scenarios
Extended GWO [51]		0,09		Compared to the conventional GWO method EGWO has smaller power oscillations and close to none.
GWO [50]	0,55	-	98%	The losses generated are less with the use of soft switching buck converter

3.6. Grey Wolf Optimization (GWO)

The Grey Wolf Optimization (GWO) algorithm adopts the behavior of the grey wolf pack in terms of its hunting expertise. The paramters of hunting adopted are speed, effectiveness and a very dominant leadership trait. Gray wolves are considered to be at the top of the natural food chain and live in packs. There are four types of gray wolf packs, namely alpha (α), beta (β), delta (δ), and omega (ω). The omega (ω) wolf is considered to be the weakest. The optimization process includes the stages of stalking the prey, chasing and approaching, then encircling and attacking the prey. In the GWO process, hunting is considered as GMPP. GWO has the advantages of achieving a better trade-off between exploration and exploitation compared to other algorithms as well as being able to suppress power oscillations[49]

In [50], the tracking result using GWO has a faster tracking time of up to 0.2 seconds compared to the incremental conductance algorithm. The efficiency of GWO reached 98% compared to the IC method under dynamic change environmental conditions. In the [51] EGWO method was developed under dynamic change environmental conditions. The improvements in EGWO are strengthening the balance of exploration and convergence speed of the algorithm which includes 3 dynamic coefficients to control the rate of exploration, increasing diversity with finer population initialization and utilizing the population mean position to update the solution. As a result of EGWO in dynamic environmental conditions, one of which is PSC, it has high adaptability, fast response time, minimal power fluctuations around MPP, has good stability and efficiency. In Table 5 presents several studies using the Grey Wolf Optimization method.

4. Conclusion

In this review, the application of optimization-based MPPT methods in tracking the Global Maximum Power Point (GMPP) during Partial Shading Condition (PSC) has been thoroughly presented. Through both simulation and experimental validation, these methods demonstrate superior performance compared to conventional approaches. Optimization-based MPPT techniques exhibit remarkable tracking speeds ranging from 0.01 to 1.3 seconds, exceptional tracking stability with negligible voltage oscillations, and outstanding efficiency levels reaching up to 99.99%.

Furthermore, PSC significantly disrupts photovoltaic (PV) systems by introducing multiple local maxima, reducing power yield, and risking permanent damage such as hotspot formation. To mitigate these challenges, metaheuristic optimization methods—including Particle Swarm Optimization (PSO), Cuckoo Search Algorithm (CSA), Artificial Bee Colony (ABC), Ant Colony Optimization (ACO), and Grey Wolf Optimization (GWO)—offer scientifically robust and adaptive control strategies. Each method brings unique strengths: PSO rapidly navigates complex search spaces; CSA leverages Levy flights for global convergence; ABC optimizes based on decentralized swarm behavior; ACO efficiently follows optimized pheromone trails; and GWO balances exploration and exploitation through dynamic leadership modeling.

Together, these optimization algorithms significantly enhance the resilience and accuracy of PV systems under dynamic environmental conditions, particularly PSC. They not only prevent power losses and instability but also contribute to the design of intelligent, scalable, and cost-effective solar energy systems suited for real-world deployment.

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