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Maximum Power Point Tracking Algorithms for Solar-PV Systems: A Review

David Joseph[1], Yusuf Jibril[1], Ibrahim Abdulwahab[1], Umar Abubakar[2]*

[1]Department of Electrical Engineering, Ahmadu Bello University, Zaria, Nigeria
[2]Department of Computer Engineering, Ahmadu Bello University, Zaria, Nigeria
*josephelohi74@gmail.com

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ABSTRACT

The increasing demand for renewable energy solutions has positioned solar PV systems as a vital contributor to the global energy mix. However, the efficiency of Photovoltaics (PV) systems is challenged by non-linear characteristics, environmental variability, and the limitations of existing Maximum Power Point Tracking (MPPT) algorithms. Traditional MPPT methods, while simple and cost-effective, often fail under highly demanding conditions and partial shading, causing ineficiency performance. Advanced optimization techniques such as Particle Swarm Optimization (PSO) and Gray Wolf Optimizer (GWO) have demonstrated higher efficiency and adaptability but require significant computational resources. Hybrid MPPT methods, which combine the advantages of traditional and advanced techniques, have emerged as a promising solution to enhance scalability, reduce oscillations, and improve tracking accuracy. This review examines these MPPT strategies, categorizing them and highlighting their strengths, limitations, and future potential.

1. INTRODUCTION

Conventional electricity generation has predominantly relied on hydrocarbon fuels such as coal, petroleum, and natural gas. While these resources have powered industrialization and economic growth for centuries, they are finite and pose significant environmental and economic challenges [1]. The extraction, transportation, and combustion of fossil fuels release greenhouse gases, including carbon dioxide and methane, which are the main factors in global warming and climate change [2]. Furthermore, the depletion of these resources threatens energy security and global economic stability, driving the urgent need for alternative energy solutions.Renewable energy sources, including solar, wind, and hydro, have emerged as viable and sustainable alternatives to fossil fuels. These energy sources are inherently replenishable, environmentally friendly, and capable of meeting the growing global energy demand. Among these, wind energy has proven effective in areas with consistent wind patterns, while hydropower relies on abundant water resources and is a cornerstone in regions with significant river systems. Similarly, geothermal energy is harnessed in tectonically active areas where the Earth's heat can be converted into electricity. Despite the benefits of these renewable energy sources, their adoption is often constrained by geographic and environmental limitations [3].

Solar energy, on the other hand, offers a universally applicable and highly scalable solution. The Sun emits an immense and inexhaustible amount of energy, with the potential to meet global energy demands many times over. Unlike other renewable energy sources, solar energy is not geographically restricted and can be harnessed in most parts of the world, even in areas with moderate sunlight [4]. The development of solar photovoltaic (PV) systems has been instrumental in utilizing this abundant resource, offering a clean, efficient, and sustainable energy solution. Solar PV systems stand out due to several unique advantages [5]. The Sun provides more energy in one hour than the global population consumes in a year, ensuring that solar energy can play a significant role in diversifying the energy mix. These systems are highly scalable and can be applied in diverse settings, ranging from rooftop residential installations to expansive industrial solar farms, making them adaptable to both urban and rural contexts. Solar energy is also an environmentally friendly source of electricity since it generates no greenhouse gas emissions while operating, it greatly minimizes the carbon footprint and contributing to efforts against climate change [6]. Economically, after the initial installation costs, PV systems require minimal maintenance and operational expenses, making them cost-effective over the long term. Furthermore, solar systems enable individual communities, and industries to produce electricity locally, decreasing reliance on the central power grid and imported fossil fuel [7]. Despite these advantages, the widespread adoption of solar PV systems is hindered by several challenges. Key among these are the system's low energy conversion efficiency and the non-linear behavior of its current-voltage (I-V) and power-voltage (P-V) characteristics presents challenges, especially under conditions like partial shading, rapid irradiance fluctuations, and temperature variations, which can greatly impact system performance [8]. To address these issues, advanced techniques are required to maximize energy extraction from PV systems in dynamic environmental conditions.

Maximum Power Point Tracking (MPPT) techniques play a crucial role in overcoming these challenges. These algorithms dynamically adjust the operating conditions of a photovoltaic (PV) system to maintain operation at its maximum power point (MPP). Over time, various MPPT strategies have been introduced, including conventional methods such as Perturb and Observe (P&O) and Incremental Conductance (IC) to advanced optimization-based methods such as Particle Swarm Optimization (PSO) and Grey Wolf Optimization (GWO). Each of these methods offers distinct advantages and limitations in terms of tracking speed, accuracy, and adaptability to dynamic conditions [9]. This review aims to analyze the various MPPT methods employed in solar PV systems, evaluating their performance under different environmental conditions. By understanding the strengths and weaknesses of existing approaches, this study seeks to identify opportunities for advancing MPPT technologies to improve the efficiency, reliability, and scalability of solar energy systems.

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2. METHODS

Solar cells form the essential components of a photovoltaic (PV) generator, with their performance and efficiency determined by their equivalent electrical circuit. To represent solar cell behavior, several mathematical models have been developed, including the one-diode model, two-diode model, ideal diode model, three-diode model, and multi-dimensional diode-based models.

2.1. Material

These models are widely discussed in the literature and evaluated under varying conditions to understand the semiconductor's nonlinear characteristic junctions, particularly under varying temperature and solar radiation levels. The purpose of these representations is to simulate the real-world performance of solar cells in challenging environments such as semi-arid or dry regions. Solar cells generate electricity through the photovoltaic effect, where photons striking the cell produce an electric current [10]. The single-diode model, commonly used to analyze solar cell performance, is shown in **Figure 1**.

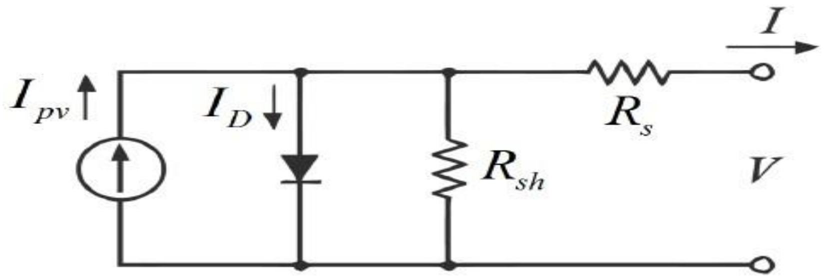

Figure 1. Equivalent Model of Single-Diode Photovoltaic Cell

This model incorporates essential parameters like series resistance (Rs), shunt resistance (R_sh), and a diode to capture the electrical behavior of a solar cell.

2.1.1 Single-Diode Solar Cell Model

The current produced by a solar cell is mathematically expressed using Kirchhoff's circuit laws, as shown in Equation (2):

$$\mathrm{I} = I_{ph} - (\exp(\frac{V + R_s I}{nN_s V_t}) - 1) - \frac{V + R_s I}{R_p} \tag{1}$$

Here, I and V represent the current and voltage output of the PV cell, I_{ph} is the photo-generated current, I_o is the diode's reverse saturation current, and is the diode's ideality factor. Additionally, V_t is the thermal voltage, which is defined in Equation (2) [11]:

$$V_t = \frac{kT}{q} \tag{2}$$

Where k is the Boltzmann constant, q is the electron charge, and T is the absolute temperature of the cell. The photo-generated current depends on solar irradiance and temperature, as described in Equation (3):

$$I_{ph} = I_{sc} + K_i(\mathrm{T} - T_{ref})\frac{G}{G_{ref}} \tag{3}$$

Here, G represents the solar irradiance on the PV surface, while G_ref denotes the reference irradiance, usually set at 1000 W/m². The short-circuit current under standard test conditions

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(STC) is given by I_{sc}, whereas K_i refers to the current temperature coefficient. Additionally, T_{ref} corresponds to the reference temperature, which is 25°C under STC.

3. TRADITIONAL MPPT ALGORITM

3.1 Perturb and Observe (P&O) Algorithm

The Perturb and Observe (P&O) algorithm is a commonly used technique in PV systems to optimize power generation under fluctuating solar radiation. It functions by slightly adjusting the PV module's operating voltage and monitoring the resulting changes in power output. The current power is continuously compared with the previous power measurement to decide whether to increase or decrease the input voltage. If the power increases, the perturbation continues in the same direction; otherwise, it reverses direction to track the Maximum Power Point (MPP). This iterative process ensures that the PV system operates at its optimal point under steady conditions [5]. Numerous studies have sought to improve the efficiency of the P&O MPPT algorithm. [13] demonstrated that optimizing sampling intervals based on the dynamic behavior of the converter can significantly enhance tracking efficiency, particularly in systems with varying load and environmental conditions. In another study, [14] developed an MPPT charge controller using the P&O algorithm for a 200 W independent PV system. By integrating a lead-acid battery into their setup, they observed substantial improvements in power tracking performance when compared to conventional charge controllers. Moreover, [15] introduced an improve adaptive P&O MPPT algorithm that achieved a global peak tracking efficiency of over 99% under partial shading scenarios. They also noted a significant increase in tracking speed, which improved by 2 to 3 times compared to conventional methods.

Further advancements include the work of [16], who proposed modifications to the P&O algorithm to enhance its performance in both steady-state and dynamic conditions. These modifications were validated through simulations in MATLAB/Simulink and demonstrated improved efficiency under various atmospheric scenarios. [17] extended the P&O algorithm's capabilities to partial shading conditions, highlighting significant improvements in tracking accuracy and implementation simplicity. Despite its widespread adoption, the P&O algorithm faces challenges, particularly in rapidly changing environmental conditions. Under such scenarios, the algorithm may fail to track the MPP accurately, leading to reduced efficiency and increased oscillations [4]. A typical flow chart for the P&O algorithm, illustrating its operational steps, is shown in **Figure 2**.

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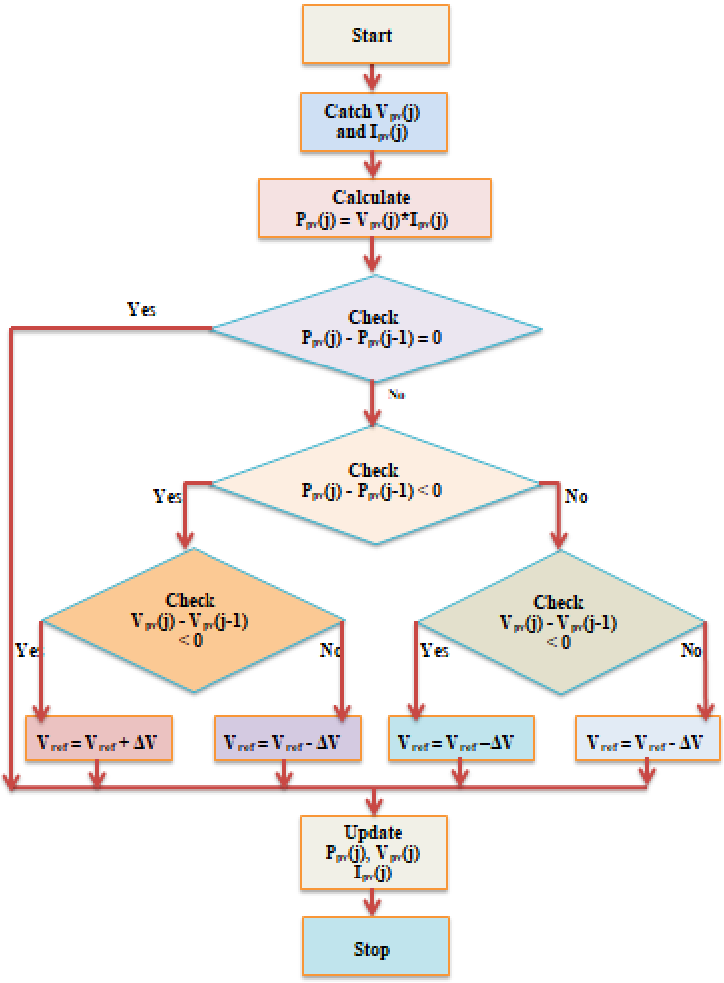

Figure 2. Flowchart for Conventional P&O MPPT Algorithm

Recent research has focused on integrating advanced optimization techniques with the P&O algorithm to address its limitations. For instance, metaheuristic-based methods such as the PSO and GA have been examined to dynamically adjust the step size and perturbation rate, thereby improving the algorithm's performance under fluctuating conditions [18]. Additionally, hybrid approaches combining P&O with machine learning algorithms are emerging, offering adaptive responses to rapidly changing irradiance and temperature levels. These advancements hold promise for next-generation PV systems intended to achieving high efficiency and robustness.

3.2 Incremental Conductance Algorithm

The Incremental Conductance (IC) algorithm identifies the Maximum Power Point (MPP) by analyzing the instantaneous power variation with regarding to the input voltage of the solar PV module. Compared to algorithms like P&O, it performs more effectively under significant variations in solar irradiation. However, this algorithm involves more complex mathematical modeling and requires additional electrical components, making its implementation more intricate [19, 20].

One of the primary limitations of the traditional IC algorithm is its inability to respond accurately to sudden variation in solar irradiance. To address this, versions of the IC algorithm have been developed, specifically targeting scenarios with sudden variations in environmental conditions. Simulation studies comparing these modified IC algorithms with their conventional counterparts demonstrate enhanced accuracy and adaptability in rapidly changing

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environments [21][19] introduced an improved IC MPPT algorithm designed to improve the efficiency and cost-effectiveness of solar PV systems. Their MATLAB/Simulink simulations revealed significant advancements in tracking performance and response time over the conventional IC algorithm. Similarly, [22] proposed an adaptive step-size IC-based MPPT method, where the step size dynamically adjusts after each iteration. This approach ensures faster convergence to the MPP without compromising tracking accuracy.

Despite these improvements, a notable drawback of the IC algorithm persists: the manual trial-and-error method for determining the voltage increment or decrement. This limitation can hinder its practical implementation and performance, particularly in dynamic conditions. Researchers continue to refine the IC algorithm to overcome these challenges and improve its applicability in real-world PV systems. **Figure 3** shows the flowchart for IC algorithm.

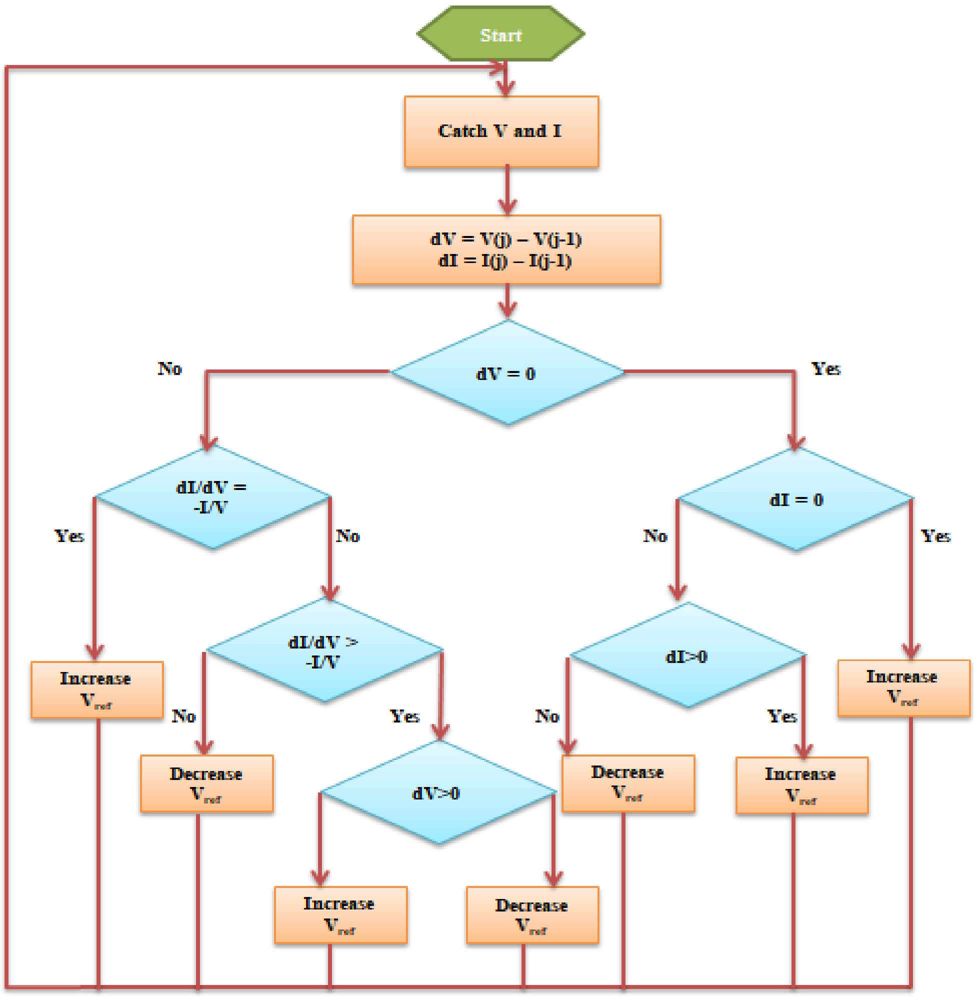

Figure 3. Flowchart of Incremental Algorithm

3.3 Hill Climbing Algorithm

The Hill Climbing (HC) algorithm is a straightforward and easily implementable MPPT technique. Unlike other algorithms, it doesn't rely on intricate mathematical models or extensive analytical studies, positioning it as the favored option for simpler PV system designs [23]. The algorithm adjusts the operating duty ratio of the DC-DC converter to locate and maintain the MPP. Its simplicity and ease of implementation are key advantages, especially in scenarios where computational resources are limited.

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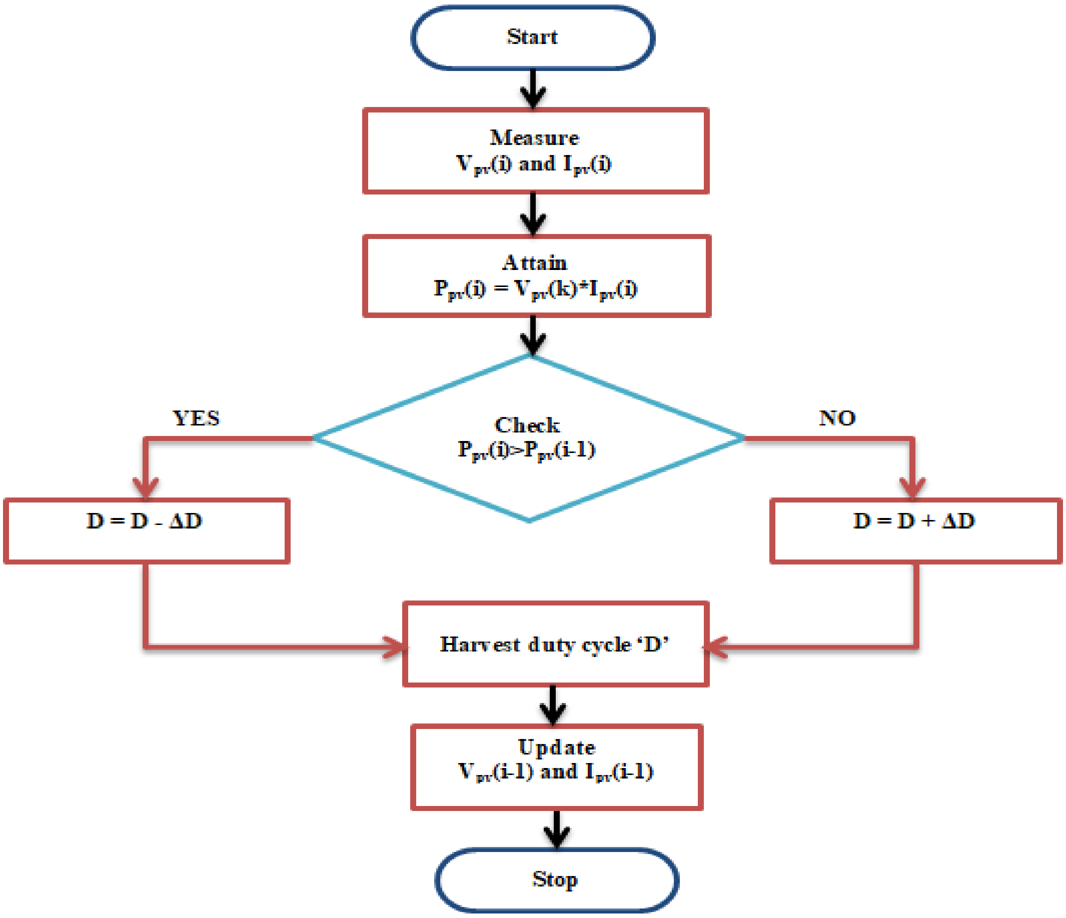

Figure 4. Flowchart for HC MPPT Algorithm

In the HC algorithm, the operating duty ratio is incremented or decremented based on the observed power output. If an increase in duty cycle results in higher power, the oscillation proceeds without changing direction. Conversely, if the power drop, the algorithm reverses the oscillation direction. This approach guarantee that the system converges toward the MPP under stable environmental conditions [24].

Although simple, the HC algorithm has certain limitations. It is prone to oscillations around the MPP, leading to minor power losses. Like the P&O algorithm, it may face difficulties to accurately track the MPP during rapid changes in solar irradiance or temperature. To address these challenges, researchers have proposed enhancements to the HC algorithm. These include adaptive step-size techniques to reduce oscillations and hybrid methods that combine HC with more advanced optimization algorithms like PSO or ANNs to improve tracking accuracy and response time [25].

Furthermore, the HC algorithm is well-suited for integration with low-cost PV systems, where simplicity and cost-effectiveness are priorities. Its reliance on the converter's duty cycle rather than complex mathematical computations makes it an attractive option for standalone and small-scale applications [26]. However, ongoing research focuses on refining its performance in dynamic conditions to expand its applicability to larger and more sophisticated PV systems.

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4. OPTIMIZATION ALGORITHM

4.1 Particle Swarm Optimization (PSO) In MPPT For Solar PV Systems

Particle Swarm Optimization (PSO) is an iterative method that provides optimized solutions to problems with high tracking speed, enabling efficient operation under varying weather conditions. PSO is known for its strong capability to identify the global optimal solution, independence from specific system configurations, minimal parameter tuning requirements, and computational efficiency without involving complex mathematical derivatives. The operational principles of the PSO algorithm are thoroughly reviewed by [27], focusing on criteria such as convergence speed, search space exploration, initialization system variable, effectiveness, and operational performance under both uniform and partial shading conditions.

While conventional PSO-based MPPT algorithms are effective, they have limitations, including slower convergence and oscillations during the search process. To address these issues, several advanced PSO variants have been created in recent years. For example, [28] proposed a novel MPPT method using the PSO algorithm, simulated it in MATLAB/Simulink, and compared its performance with P&O and Incremental Conductance (IC) methods. The results demonstrated superior tracking speed and stability, particularly during rapid environmental changes. Similarly, [29] introduced a two-stage PSO-based MPPT approach for controlling solar PV systems using a buck converter, achieving higher power output compared to traditional P&O and PSO algorithms.

Numerous studies have proposed and evaluated improved PSO-based MPPT methods. [30] developed enhanced PSO algorithms, simulated them in MATLAB/Simulink, and observed significant performance improvements over traditional methods. These advancements underscore the potential of PSO in maximizing MPPT for solar PV systems.

4.2 Genetic Algorithm

The Genetic Algorithm (GA) is a powerful optimization method influenced by the natural procedure of evolution, including selection, crossover, and mutation. In the context of MPPT, GA is particularly effective due to its global search capability, enabling it to avoid the issue of getting trapped in local maxima—a common challenge in complex PV systems under partial shading conditions.

A notable application is presented by [31], where GA was implemented to identify the global maximum power point (GMPP) under partial shading scenarios. Their results demonstrated that GA could efficiently handle the non-linear and multi-modal nature of PV power curves, ensuring that the system consistently tracks the highest power output.

Other studies, such as [32], explored hybrid GA-based MPPT approaches combined with fuzzy logic control. This hybridization further enhanced convergence speed and improved overall system stability, showing the adaptability of GA in integrating with other optimization techniques. Its capability to manage non-linear and discontinuous power curves. Strong global search capabilities, even in difficult scenarios such as partial shading. Flexibility to adapt to hybrid systems for enhanced performance.

4.3 Cuckoo Search Algorithm

The Cuckoo Search (CS) algorithm, developed by Yang and Deb, draws inspiration from the behavior of cuckoo birds, particularly their strategy of depositing eggs in the nests of different birds [33]. This strategy is used as a metaphor for a metaheuristic optimization

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method. Cuckoos select the nests of other birds to lay their eggs, aiming to position them in a way that increases the chances of survival for the next generation of cuckoos. A flowchart depicting the CS algorithm is shown in **Figure 5**.

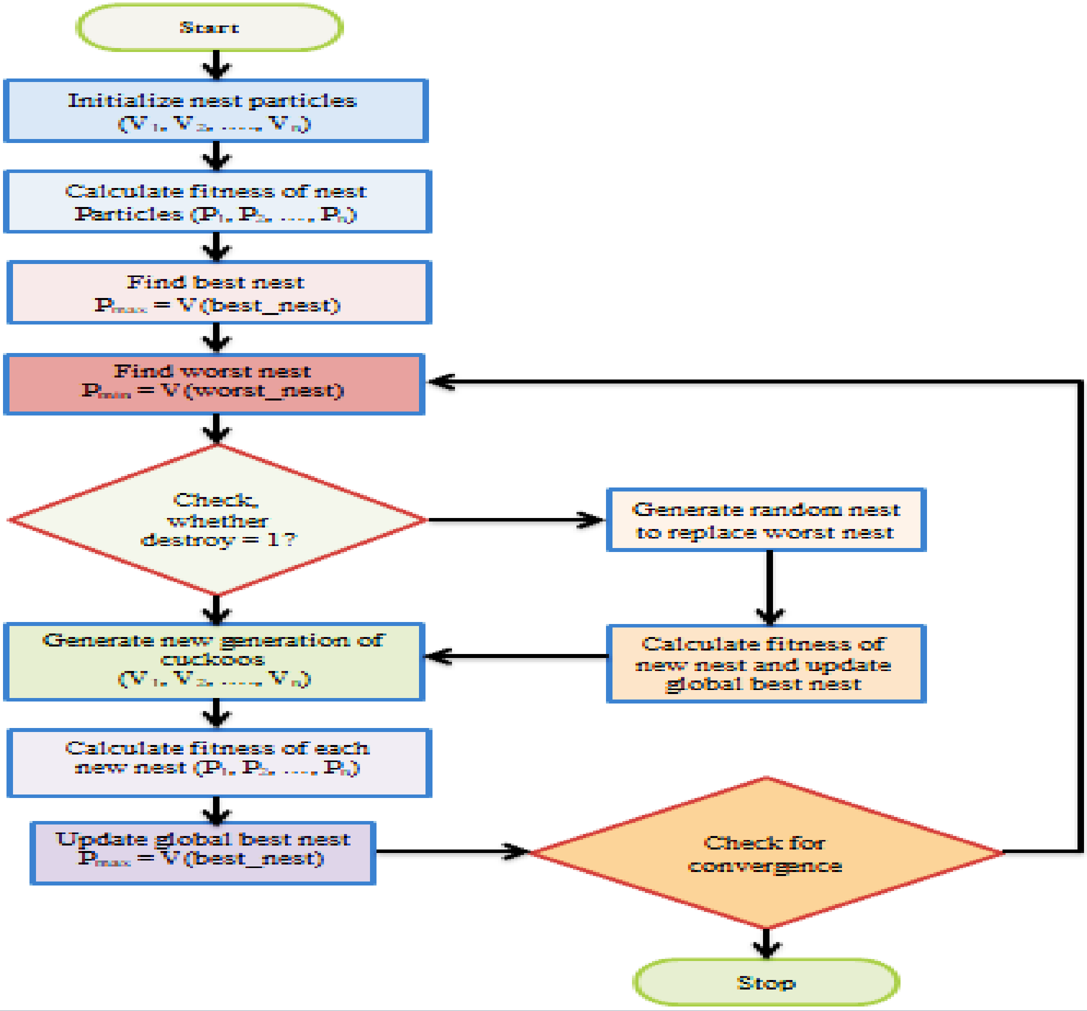

Figure 5. Flowchart for CS Algorithm

[34] investigated the use of CS for MPPT in PV systems, emphasizing its capacity to attain fast convergence to the global maximum power point (GMPP). The study revealed that CS could effectively reduce steady-state power oscillations, resulting in smoother power output and enhanced system efficiency. Unlike conventional methods, CS's global search capability allowed it to perform consistently well in highly non-linear and partially shaded conditions.

In addition, [35] developed an improved CS to overcome the constraints of MPPT The MPPT algorithm demonstrated enhance tracking speed in dynamic changing environments and improved accuracy in locating the GMPP. The study highlighted the adaptability of CS when compared with other metaheuristic techniques, making it a versatile tool for complex PV systems. The primary strengths Of Cs for MPPT Include: Fast convergence to the GMPP with high accuracy. Strong exploration capabilities, reducing the likelihood of getting trapped in local optima. Flexibility to be combined with other algorithm to enhance performances further [35].

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4.4 Grey Wolf Optimization Algorithm

The Grey Wolf Optimization (GWO) algorithm is modeled after the hunting strategies and social dynamic of grey wolves. A GWO-based MPPT algorithm, designed for solar PV systems utilizing a single-ended primary-inductor converter, was simulated in MATLAB/Simulink. The results demonstrated improved performance, including faster response times and better steady-state performance, as reported by [36]. **Figure 6** illustrates the flowchart for the GWO algorithm.

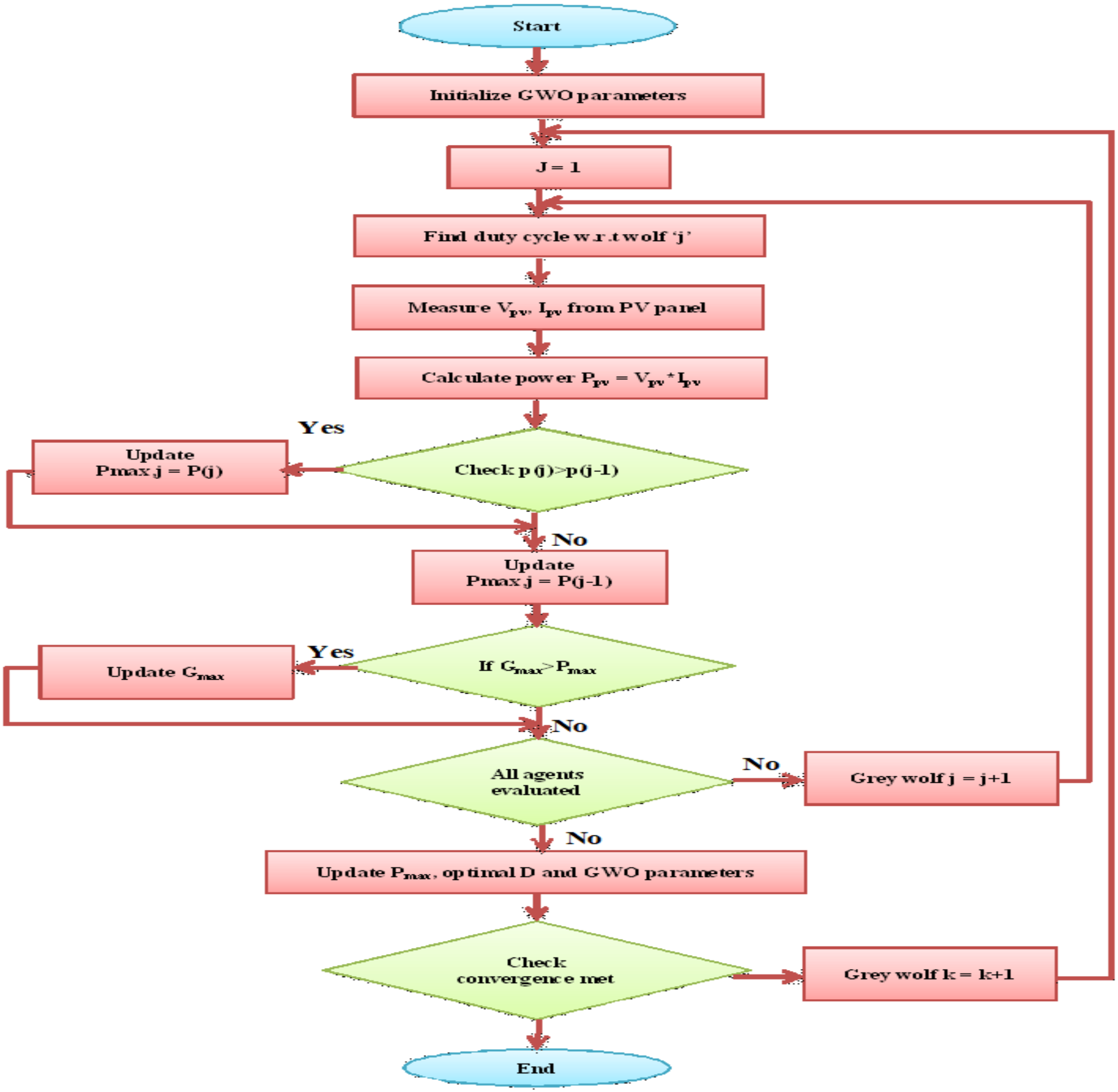

Figure 6. Flowchart for GWO Algorithm

The Particle Swarm Optimization (PSO) and Grey Wolf Optimizer (GWO) algorithms were analyzed for tracking the maximum power point (MP) of a solar PV system under partial shading conditions. Their performance was evaluated in MATLAB/Simulink, with findings indicating that GWO surpasses PSO, as reported in [37].

For MPPT design in solar PV systems, the Grey Wolf Optimizer (GWO) algorithm overcomes various drawbacks of the Perturb and Observe (P&O) method, including steady-state oscillations, tracking efficiency, and transient response under partial shading conditions.

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Findings suggest that the GWO-based MPPT approach delivers superior performance compared to other algorithms, as noted in [38].

Additionally, two new MPPT algorithms, the Whale Optimization Algorithm (WOA) and GWO, were introduced for solar PV systems. These algorithms demonstrated better performance than traditional methods in terms of ripple, overshoot, and response time, as reported by [39, 40].

4.5 Sine and Cosine Algorithm (SCA)

The Sine and Cosine Algorithm (SCA) has emerged as a promising approach for solving MPPT problems due to its ability to effectively balance exploration and exploitation. One significant application of SCA is to tackle the challenges caused by partial shading conditions in photovoltaic (PV) systems. In these conditions several local maxima are created in the power-voltage (P-V) curve, complicating the identification of the global MPP. [41] developed a fast and accurate MPPT algorithm based on SCA, which demonstrated superior performance in locating the global MPP in contrast to conventional methods like the P&O and INC algorithms. The proposed method achieved faster convergence and higher tracking accuracy, even in the presence of shading.

In addition, the hybridization of SCA with other optimization techniques has shown great promise in improving MPPT performance. For instance, [42] introduced a hybrid Grey Wolf Optimizer-Sine Cosine Algorithm (HGWOSCA) for PV systems. This hybrid approach enhanced convergence speed and tracking efficiency under dynamic weather conditions, outperforming standalone algorithms. Beyond PV systems, SCA has also been employed in optimizing the performance of thermoelectric generators.

The success of SCA in MPPT applications can be attributed to its global search capability, which enables it to explore the solution space effectively and avoid being trapped in local optima—an essential feature when dealing with partial shading. Furthermore, its simplicity, stemming from its reliance on basic sine and cosine functions, makes it easy to implement [43]. SCA's flexibility also allows it to be hybridized with other algorithms to tackle challenges such as nonlinear system behavior and rapidly changing environmental conditions [42]. In conclusion, the Sine and Cosine Algorithm has demonstrated significant potential in solving MPPT problems, particularly under challenging scenarios like partial shading and dynamic weather. Its robustness, efficiency, and adaptability make it a valuable tool for optimizing PV system performance.

4.6 Artificial Neural Networks (ANN)

The primary goal of Artificial Neural Networks (ANN) is to determine a new duty cycle value in response to small changes in solar irradiance and temperature in order to achieve the Maximum Power Point (MPP), without relying on complex mathematical models for non-linear problems. This process is achieved through training with the Levenberg-Marquardt algorithm, as discussed by [44]. An ANN model using the Levenberg-Marquardt algorithm, trained on 1000 data points with a two-layer network, has demonstrated improved performance, as noted by [45].

In other studies, a three-layer ANN network has been designed to track the maximum voltage from a solar PV panel, eliminating the need for voltage and current sensors, as well as complex mathematical computations, thereby achieving higher efficiency (Suganya et al., 2014). Furthermore, [46] introduced a cascading two-layer ANN model to track the MPP from

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a solar PV system, assuming 10 neurons per layer. The generated duty cycle, based on binary outputs, is used to control the inverter's switching operations, as highlighted in [47].

4.7 Hybrid MPPT Algorithms

4.7.1 Hybrid PSO-CS

The Particle Swam Optimization-Cuckoo Search (PSO-CS) hybrid algorithm is designed to address complex non-linear optimization problems achieved by integrating the Particle Swarm Optimization (PSO) iteration strategy with the Cuckoo Search (CS) method. According to [48], the flowchart for the PSO-CS hybrid MPPT algorithm is depicted in **Figure 7**.

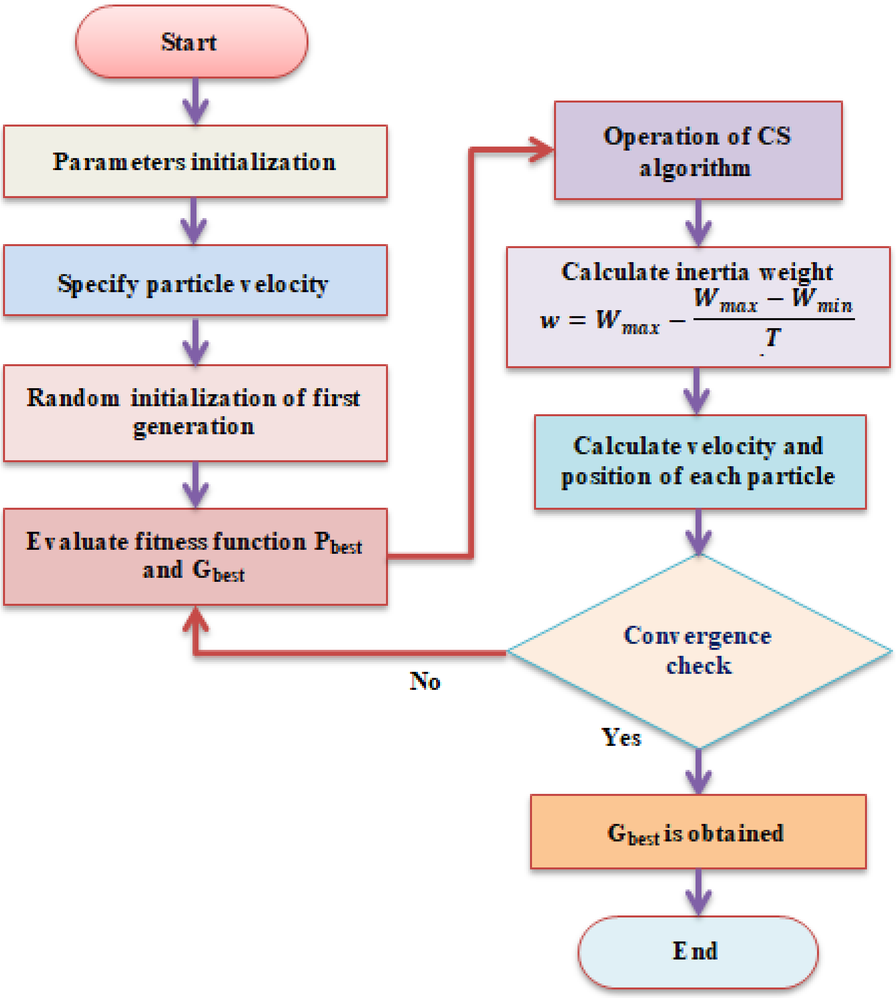

Figure 7. Hybrid PSO-CS Flowchart

In this approach, the optimization problem is broken down into several subcomponents, which are then enhanced using the standard CS method.To improve the PSO algorithm's performance the random search mechanism is substituted with Lev flight, forming the hybrid PSO-CS algorithm. In this method, the search is carried out by adjusting fixed parameters such as random 1, random 2, w1c1, and w2c2. The length of the random steps is modified through Levy flights.

The hybrid PSO-CS algorithm demonstrates greater reliability and effectiveness compared to both the PSO and CS algorithms, particularly in finding global optimal solutions for non-linear problems. It was observed that the hybrid PSO-CS algorithm outperforms the individual PSO and CS algorithms in terms of convergence speed, accuracy, and overall efficiency.

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4.8 Comparison Between MPPT Types

Each MPPT approach offers unique advantages and limitations, and recognizing these compromises is essential for choosing or developing the optimal choice algorithm for a given application.

4.8.1 Traditional Algorithms

Traditional MPPT algorithms, such as P&O and IC, are commonly utilized because their simplicity, low computational requirements, and easy to implement. These characteristics make them particularly suitable for low-cost or small-scale PV systems. For instance, the P&O algorithm performs well under steady-state conditions and is easy to implement on microcontroller-based systems. However, it suffers from oscillations around the maximum power point (MPP) and poor tracking performance under rapidly changing environmental conditions. Similarly, IC provides better accuracy in dynamic conditions by considering the gradient of the power curve but at the cost of increased computational complexity, making it less feasible for cost-sensitive applications [49].

Additionally, while OCV and SCC methods are highly simple and require minimal processing power, their reliance on approximate values of the MPP often leads to significant tracking inaccuracies, particularly in non-uniform or rapidly changing conditions.

4.8.2 Optimization Techniques

Optimization-based algorithms, such as PSO, GA, and Grey GWO, offer significant improvements over traditional methods in terms of global search capability and the ability to avoid local minima. PSO, for example, is renowned for its fast convergence and adaptability to dynamic conditions, making it an excellent candidate for large-scale or high-performance PV systems. However, it can experience convergence delays or become trapped in suboptimal solutions under highly variable conditions [50].

GA is another popular optimization technique, leveraging evolutionary principles to provide high accuracy in locating the MPP. Nevertheless, its reliance on multiple iterations for crossover and mutation can lead to increase computational demands, making it less ideal for real-time applications [51].

Optimization techniques, while highly accurate, generally require more sophisticated hardware and computational power, limiting their application in low-cost PV systems. Their performance is also influenced by the choice of algorithm parameters, which may require iterative testing and optimization for specific scenarios.

4.8.3 Machine Learning Algorithms

Machine learning-based MPPT algorithms, like Artificial Neural Networks (ANNs) and Reinforcement Learning (RL), are gaining attention for their capacity to manage complex, non-linear relationships between PV system inputs (e.g., irradiance and temperature) and outputs (power). ANNs, for example, can be trained on historical data to predict the MPP with high precision, even under variable and partially shaded conditions. However, their efficiency is heavily reliant on the accuracy and quantity of training data, and their computational demands are significantly higher than traditional or optimization-based methods [52].

Reinforcement learning, a subset of machine learning, offers real-time adaptability to dynamic environments by learning from ongoing system feedback. While promising, it often

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requires substantial computational power and can suffer from long training periods before achieving optimal performance [53].

4.8.4 Hybrid Algorithms

Hybrid algorithms integrate the strengths of multiple MPPT techniques, such as integrating traditional algorithms with optimization or machine learning methods. For example, a hybrid P&O-PSO approach utilizes the simplicity of P&O for initial tracking and leverages PSO for fine-tuning, resulting in faster convergence and reduced oscillations at the MPP [54]. Similarly, combining IC with GWO can improve tracking accuracy and robustness under dynamic conditions while minimizing computational overhead.

The primary advantage of hybrid algorithms is their ability to balance trade-offs between accuracy, speed, and computational complexity. By blending complementary techniques, hybrid methods can overcome the limitations of individual algorithms, making them particularly suitable for modern PV systems with variable and complex operating environments [55].

4.9 Key Insights

Key Insights from this in-depth review are:

- Simplicity vs. Complexity: Traditional algorithms excel in simplicity and cost-effectiveness, while optimization and machine learning techniques offer superior accuracy and adaptability at the expense of higher computational requirements.
- Scalability: Optimization and hybrid algorithms are better suited for large-scale PV systems due to their enhanced robustness and adaptability.
- Dynamic Environments: Hybrid approaches, particularly those integrating advanced optimization techniques, are the most promising for handling rapidly changing irradiance and temperature conditions.
- Cost Sensitivity: For low-cost applications, traditional algorithms or simplified versions of optimization techniques remain viable options, albeit with reduced performance under dynamic conditions.

Ultimately, selecting an MPPT algorithm depends on the PV system's specific requirements, including system size, budget constraints, and environmental variability.

4.10 Issues that still remain to be solved

Issues that still remain to be solved are:

- Fluctuate around the maximum power point: Many MPPT algorithms, particularly traditional ones like P&O, suffer from stable oscillations around the MPP. These oscillations result in power losses, reducing overall system efficiency. Advanced optimization-based algorithms attempt to minimize this issue but often do so at the cost of increased computational complexity [55].
- Dynamic Environmental Conditions: Rapid changes in irradiance and temperature, such as those caused by passing clouds or partial shading, remain a significant challenge for most MPPT techniques. Traditional algorithms struggle to track the MPP effectively under these conditions due to their slower response times. While optimization and machine learning-based methods show better adaptability, they require real-time computation and sophisticated hardware, which can limit their practical implementation.

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- Trade-offs Between Efficiency and cost: Advanced algorithms like PSO and Genetic Algorithm (GA) offer high tracking accuracy and adaptability. However, their computational requirements often necessitate expensive hardware such as high-performance microcontrollers or digital signal processors (DSPs). This cost factor makes these algorithms less feasible for low-budget or small-scale PV systems [56].
- Scalability for High-Power Systems: Many MPPT techniques are designed and tested on small-scale PV systems. Scaling these algorithms to high-power PV systems, such as those used in industrial or utility-scale applications, often introduces new challenges. Issues like increased power losses, longer convergence times, and the need for more robust hardware remain largely unresolved.
- Longevity and Reliability: The continuous operation of MPPT algorithms can cause thermal and electrical stresses on PV system components, particularly in harsh environmental conditions. These stresses can reduce the lifespan and reliability of the system. Addressing these issues requires incorporating strategies for thermal management and stress reduction, which are still underexplored in current MPPT research [57].
- Effectiveness Under Partial Shading Conditions: Partial shading, where only parts of the PV array receive sunlight, creates several local peaks on the power-voltage curve. Many traditional and optimization-based MPPT algorithms struggle to distinguish the global MPP from local maxima, leading to suboptimal power extraction. Recent advancements like hybrid and machine learning approaches have shown promise, but they require further refinement and validation under diverse real-world conditions.
- Integration with Smart Grids and Energy Storage Systems: With the growing adoption of smart grids and battery energy storage systems, MPPT algorithms need to be more versatile. They must account for grid requirements, such as voltage and frequency regulation, while ensuring optimal battery charging. Current MPPT research often focuses on standalone systems, leaving integration with modern grid infrastructures as an open area for exploration.
- Lack of Standardization: There is no universal framework for evaluating and comparing MPPT algorithms. Performance metrics, such as efficiency, tracking speed, and adaptability, vary across studies, making it difficult to benchmark algorithms against one another. Developing standardized test conditions and performance criteria is essential for advancing the field [58].

By addressing these challenges, researchers can further enhance the performance, reliability, and scalability of MPPT algorithms, ensuring their suitability for the diverse and evolving demands of solar PV systems.

5. DISCUSSION

This review highlights the significant evolution of MPPT techniques in photovoltaic systems. One of the key advantages of optimization-based and hybrid methods is their ability to achieve faster convergence to the Maximum Power Point (MPP), even under partial shading or rapidly changing irradiance. Techniques like Particle Swarm Optimization (PSO), Grey Wolf Optimization (GWO), and hybrid PSO-CS approaches demonstrate superior tracking accuracy, global search ability, and improved system efficiency. These methods are capable of adapting to dynamic environmental conditions, which traditional algorithms like P&O and IC often struggle to handle.

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However, the application of such methods also introduces limitations. Notably, increased computational complexity can hinder implementation in cost-sensitive or low-resource environments. Some algorithms, particularly machine learning-based models like ANNs, require extensive training and large datasets to achieve high accuracy. Furthermore, while hybrid methods offer adaptability and robustness, they may demand advanced control hardware and sophisticated tuning, making real-world deployment more challenging.

The novelty of this review lies in its structured categorization of MPPT strategies, especially in hybrid optimization methods. Unlike previous studies that often focus on traditional or single-optimization algorithms, this paper emphasizes emerging hybrid trends and highlights comparative performance under real-world challenges such as dynamic weather conditions, system longevity, and scalability. This work builds upon existing literature by offering clear insights into trade-offs between cost, efficiency, and adaptability, providing a valuable reference for future research and practical implementation.

6. CONCLUSION

This review has explored the evolution of MPPT tracking method in solar PV systems, ranging from traditional methods like P&O and IC to optimization-based, machine learning-driven, and hybrid approaches. Each method was analyzed for its performance, adaptability, computational complexity, and scalability. While traditional algorithms offer simplicity and cost-effectiveness, their limitations in tracking efficiency, particularly under dynamic conditions, highlight the need for advanced approaches. Optimization algorithms and machine learning techniques, though highly efficient, often require significant computational resources and specialized hardware, limiting their practical application in cost-sensitive or large-scale systems.

The hybrid approach, which combines traditional methods with advanced optimization or machine learning techniques, has emerged as the most promising solution. By leveraging the strengths of both approaches, hybrid methods can achieve faster tracking speeds, improved accuracy, and robustness under multiple conditions, including partial shading and rapid environmental changes. Despite these advancements, challenges such as system longevity, scalability, cost-effectiveness, and standardization remain key areas for improvement in MPPT research.

7. AUTHORS' NOTE

The authors declares no conflict of interest regarding this publication and confirm that the paper is free of plagiarism.

8. AUTHORS' CONTRIBUTION

David Joseph: Conceptualization, Methodology, Writing Original Draft, Investigation; Yusuf Jibril: Formal Analysis, Writing Original Draft, Supervision; Ibrahim Abdulwahab: Data Curation, Review & Editing, Investigation; Umar Abubakar: Software Review & Editing, Investigation.

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