A Comprehensive Comparative Analysis of Mppt Techniques: Conventional, Soft Computing, and Metaheuristic Approaches

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Abstract:Photovoltaic (PV) systems have gained widespread popularity as a clean and sustainable source of energy. However, their operational efficiency is often compromised under real-world conditions such as partial shading, which disrupts the generation of maximum power. This review paper investigates the application of meta-heuristic-based Robust Maximum Power Point Tracking (MPPT) algorithms to improve the operational efficiency of PV installations under partially shaded conditions. Various meta-heuristic algorithms including Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Differential Evolution (DE) are evaluated in terms of their speed, accuracy, and reliability for tracking the Maximum Power Point (MPP) under challenging environmental conditions. The study reveals that meta-heuristic-based MPPT algorithms offer significant advantages over traditional techniques such as Perturb and Observe (P&O) and Incremental Conductance (IncCond), notably in reducing oscillations around the MPP and improving the transient response. The paper further identifies the strengths and weaknesses of each algorithm, offering valuable insights for researchers and engineers striving to optimize partially shaded PV installations. The review concludes by suggesting future research directions that can further harness the potential of meta-heuristic algorithms for robust and efficient MPPT in solar PV systems.

Keywords:*Photovoltaic Systems, Maximum Power Point Tracking (MPPT), Partial Shading, Meta-heuristic Algorithms, Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Differential Evolution (DE), Operational Efficiency, Robust Control, Transient Response.*

1. Introduction

The relentless pursuit of sustainable energy solutions has led to a substantial interest in photovoltaic (PV) systems. Solar energy, harnessed through these systems, provides a clean and inexhaustible resource with minimal environmental impact. However, the operational efficiency of PV systems is often compromised under varying environmental conditions, most notably, partial shading. Partial shading occurs when shadows from nearby objects, clouds, or even adjacent solar panels obstruct the sunlight, thereby affecting the power output. Traditional Maximum Power Point Tracking (MPPT) techniques such as Perturb and Observe (P&O) and Incremental Conductance (IncCond) struggle to maintain optimal performance under such challenging conditions.

To address these challenges, researchers and engineers are increasingly turning to meta-heuristic algorithms, such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Differential Evolution (DE), as alternatives for robust MPPT strategies. These algorithms offer more intelligent search capabilities and quicker convergence to the Maximum Power Point (MPP), thereby improving the system's operational efficiency..

The global push towards renewable energy sources has been driven by a heightened awareness of climate change and the need to reduce reliance on fossil fuels. Among renewable energy technologies, photovoltaic (PV) systems have gained significant attention due to their direct conversion of sunlight into electricity, scalability, and low operational cost. Despite these advantages, PV installations face efficiency challenges due to environmental and operational conditions. One of the most prominent issues affecting the efficiency is partial shading, where one or more PV panels are covered by shadows from clouds, adjacent buildings, or even leaves. Under these conditions, the power-voltage curve becomes non-linear and multi-modal, posing a challenge for traditional Maximum Power Point Tracking (MPPT) techniques such as Perturb and Observe (P&O) and Incremental Conductance (IncCond).

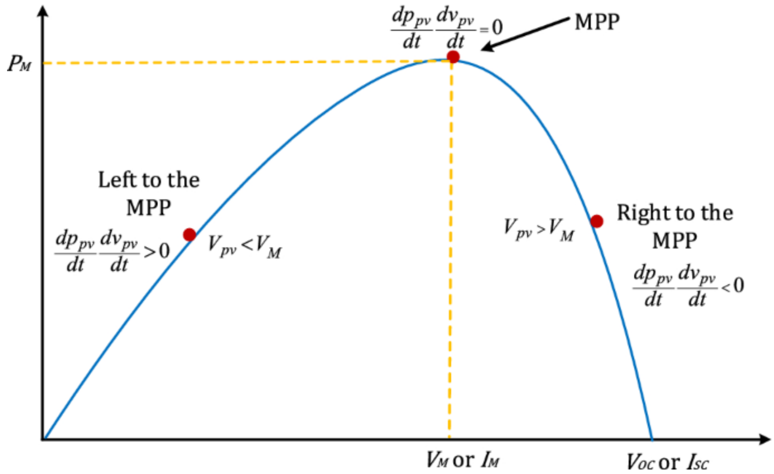

Figure 1: Relevance of MPPT on Solar PV System Power Output

Traditional MPPT techniques have been widely used due to their simplicity and ease of implementation. However, they possess inherent limitations in dealing with complex, non-linear, and dynamically changing environments such as partial shading conditions. These algorithms often get trapped in local maxima and exhibit oscillatory behavior, leading to sub-optimal energy harvest and system inefficiency. Therefore, there is an increasing need for advanced MPPT algorithms that are robust, accurate, and quick to converge to the global maximum point.Meta-heuristic algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Differential Evolution (DE) have been identified as promising alternatives to traditional MPPT methods. These algorithms are inspired by biological, physical, or social phenomena and are inherently capable of searching large, complex solution spaces. They can adapt to dynamically changing environments, offer better convergence properties, and have the ability to escape local maxima. Therefore, they have found application in solving various optimization problems, including the MPPT for PV systems under partial shading conditions.A number of studies have demonstrated the efficiency of meta-heuristic algorithms in MPPT applications. Researchers have examined various aspects such as convergence speed, computational complexity, and robustness under fluctuating conditions. However, there is a gap in the literature that systematically reviews and compares the performance of these algorithms specifically under partial shading conditions.The primary objective of this review paper is to critically assess the current state-of-the-art meta-heuristic-based robust MPPT algorithms, with an emphasis on partially shaded PV systems. The paper aims to evaluate these methods based on several key performance indicators, including but not limited to, tracking speed, tracking accuracy, computational overhead, and adaptability to environmental changes. The scope of this review extends from the fundamental theories underlying meta-heuristic algorithms to their practical implementation and performance evaluation in real-world scenarios.

The research questions guiding this review include:

1. How do meta-heuristic-based MPPT algorithms compare to traditional methods in terms of operational efficiency under partial shading conditions?

2. What are the strengths and weaknesses of each meta-heuristic algorithm in the context of partially shaded PV installations?

3. How do different meta-heuristic algorithms perform in terms of computational complexity, convergence speed, and robustness?

4. What are the future prospects and research directions in improving MPPT performance using meta-heuristic algorithms?

The remainder of this paper is organized as follows: The next section provides an in-depth examination of the challenges associated with partially shaded PV systems. Following this, we discuss the basic principles and limitations of traditional MPPT techniques. The subsequent section presents an overview of the meta-heuristic algorithms and their applications in MPPT. The final sections comprise a comparative analysis, summary of findings, and suggestions for future research avenues.By offering a detailed evaluation of meta-heuristic-based robust MPPT algorithms, this review aims to contribute to ongoing research efforts aimed at optimizing the operational efficiency of partially shaded PV installations. We intend to clarify the conditions under which each algorithm performs best and identify opportunities for further advancements in this field.

2. Maximum Power Point Tracking

Maximum Power Point Tracking (MPPT) is a critical technique used in photovoltaic (PV) systems to maximize the electrical power output from a PV cell, module, or array. The electrical characteristics of PV cells are heavily dependent on environmental conditions, such as solar irradiance and temperature, which in turn influence the output power. The MPPT algorithm continuously adjusts the operating point of the PV system to ensure it operates at the maximum power point (MPP), thus extracting the maximum available power

Understanding the power-voltage (P-V) and current-voltage (I-V) characteristics of a PV cell is fundamental to grasping the importance of MPPT. A typical I-V curve of a solar cell shows that the current decreases almost linearly as the voltage increases. On the other hand, the P-V curve shows a peak, representing the maximum power point (MPP). The voltage and current at this point are known as the MPP voltage

1. **Perturb and Observe (P&O):** This is the simplest and most commonly used MPPT algorithm. It works by perturbing (increasing or decreasing) the system's operating voltage and observing the resulting change in power. If the power increases, the perturbation continues in the same direction; otherwise, it reverses. However, P&O tends to oscillate around the MPP, especially under rapidly changing conditions, and may not be efficient under partial shading.

The principle behind P&O is relatively straightforward. It starts with a perturbation in the duty cycle, voltage, or current and then observes how the power P changes relative to the perturbation.

$$\Delta P - P_{\text{new}} - P_{\text{old}}$$
$$\Delta V - V_{\text{new}} - V_{\text{old}}$$

Based on ΔP and ΔV :

- If $\Delta P > 0$ and $\Delta V > 0$, or $\Delta P < 0$ and $\Delta V < 0$, the system moves in the direction of increasing V to reach the MPP.

- If $\Delta P > 0$ and $\Delta V < 0$, or $\Delta P < 0$ and $\Delta V > 0$, the system moves in the direction of decreasing V to reach the MPP.

2. **Incremental Conductance (IncCond):** This method is an improvement over P&O and uses the instantaneous conductance (I/V) and incremental conductance (ΔI/ΔV) to find the MPP. The algorithm calculates these values and adjusts the voltage accordingly to reach the MPP. IncCond is more accurate than P&O but requires more complex calculations.

The Incremental Conductance method uses instantaneous conductance I/V and incremental conductance $\Delta I/\Delta V$ to locate the MPP. Mathematically, it is determined by the following conditions:

$$\text{At MPP: } \frac{dI}{dV} - -\frac{I}{V}$$
$$\text{Away from MPP: } \frac{dI}{dV} + -\frac{I}{V}$$

So, using incremental and instantaneous conductance:

- If $\Delta I/\Delta V - -I/V$, the PV system is at the MPP.
- If $\Delta I/\Delta V > -I/V$, the system should increase the voltage.
- If $\Delta I/\Delta V < -I/V$, the system should decrease the voltage.

Meta-heuristic Algorithms for MPPT

1. **Particle Swarm Optimization (PSO):** In PSO, multiple "particles" search the solution space, updating their positions based on their individual experiences and the experiences of their neighbors. The swarm collectively converges to the global maximum, allowing the system to track the MPP efficiently, even under partial shading.

PSO simulates the social behavior of birds flocking or fish schooling. The position x_i and velocity $\mathbf{v}_i$ of each particle i in a D-dimensional space are updated using:

$$\mathbf{v}_i(t+1) - w\mathbf{v}_i(t) + c_1 r_1(\mathbf{p}_i - \mathbf{x}_i(t)) + c_2 r_2(\mathbf{p}_g - \mathbf{x}_i(t))$$
$$\mathbf{x}_i(t+1) - \mathbf{x}_i(t) + \mathbf{v}_i(t+1)$$

Where $\mathbf{p}_i$ and $\mathbf{p}_g$ are the personal and global best positions, w is the inertia weight, c_1 and c_2 are cognitive and social factors, and r_1 and r_2 are random numbers between 0 and 1 . **Genetic Algorithm (GA):** GA mimics the process of natural selection. It starts with an initial population and iteratively evolves it by applying genetic operators like mutation, crossover, and selection. The algorithm is highly effective in finding the global maximum in a multi-modal landscape, making it suitable for partially shaded conditions.

2. **Differential Evolution (DE):** DE is a population-based optimization algorithm that uses differential mutation. It works by generating trial vectors through the combination of vectors randomly chosen from the population. These trial vectors compete with the existing population members, leading to a gradual convergence towards the global maximum.

In DE, trial vectors $\mathbf{u}_i$ are generated as:

$$\mathbf{u}_i - \mathbf{x}_{\text{rand }1} + F(\mathbf{x}_{\text{rand2}} - \mathbf{x}_{\text{rand}})$$

Here, $\mathbf{x}_{\text{rand }1}, \mathbf{x}_{\text{rand }2}, \mathbf{x}_{\text{rand }3}$ are randomly selected vectors from the population, and F is a scaling factor. The trial vector competes with the current vector, $\mathbf{x}_i$, based on some objective function (often power in case of MPPT). By comparing these mathematical models, one can evaluate the efficiency, convergence speed, and robustness of each algorithm, especially in the context of Maximum Power Point Tracking for photovoltaic systems.

In real-world scenarios, PV arrays are often subject to partial shading, leading to multiple local maxima in the P-V curve. Traditional MPPT techniques struggle to find the global maximum under these conditions. Meta-heuristic algorithms have shown promise in efficiently tracking the global maximum, but they also have their complexities and computational requirements.

In fluctuating environmental conditions, a robust MPPT algorithm must adapt quickly and accurately to changes in temperature and irradiance levels. A sluggish or inaccurate response not only reduces power output but may also compromise the lifespan and reliability of the entire PV system. Thus, the development of robust MPPT algorithms is essential for the overall performance and efficiency of PV systems.

3. Related Works

Major research efforts have been made in recent years to enhance Maximum Power Point Tracking (MPPT) methods for solar photovoltaic (PV) systems. Numerous research have addressed the drawbacks of traditional MPPT approaches and suggested cutting-edge ways to improve effectiveness. A modified PSO method was presented by Tanuj Sen et al. (2018) to track the global maximum power point and lessen steady-state oscillations [1]. In order to increase speed and proficiency, G. Dileep et al. (2017) introduced an adaptive PSO method, verifying its efficacy under various shading situations [2]. PSO and a PI controller were integrated in a boost converter by R. Nagarajan et al. (2018) to increase voltage output [3]. A modified PSO method was presented by Kashif Ishaque et al. (2012) to minimize oscillations after MPP and adapt to changing environmental circumstances [4]. A thorough analysis of MPPT approaches was published by Faiza Belhachat et al. (2018), which helped users choose a method based on performance criteria [5]. PSO's convergence time issue was addressed by Ali M. Eltamaly et al. (2020), who also contrasted several approaches under dynamic shading circumstances [6]. These studies jointly develop MPPT technology by providing knowledge on effective tracking, environmental change resistance, and technique choice based on performance indicators. With a focus on the rising need for increased production in partial shading circumstances [7], Makbul A. et al. (2017) provided a thorough analysis of MPPT approaches under normal and partial shading conditions. The benefits of Particle Swarm Optimization (PSO) methods over traditional ones were highlighted by Zhu Liying et al. (2017) in their analysis of several MPPT approaches under varied shading circumstances [8]. The negative impacts of partial darkening were illustrated by RozanaAlik et al. (2017), who also refined the Perturb and Observe method while highlighting its accuracy and cost-effectiveness [9]. In contrast to standard approaches, Mingxuan Mao et al. (2017) introduced a unique MPPT method that concurrently minimized steady-state oscillations and offered quicker and more precise global maximum power point tracking [10]. With a focus on steady-state accuracy and high efficiency, Gomathi B et al. (2016) proposed an incremental conductance algorithm-based Solar MPPT System and offered a comprehensive analysis of DC-DC converters [11]. The performance of the converter, PV cell modeling, I-V and P-V curves, and incremental conductance approaches were all taken into account by Mr. M. Rupesh et al.'s (2018) thorough evaluation of these techniques [12]. The Drift-Free Perturb and Observe approach was created by S. Manna et al. in 2021, and it incorporates current for improved performance in changing environmental situations [13].

In a comparative investigation of several control strategies for maximizing power extraction from solar modules, PushprajsinhThakor et al. (2014) took efficiency, steady-state behavior, and dynamic reactions into account [14]. In order to regulate a boost-boost converter robustly, Naga Swetha C et al. (2018) suggested approaches using an intelligent controller and fuzzy logic algorithm to determine the global peak power point under partial shading situations [15]. Through simulations, Bennis Ghita et al. (2018) refined PSO to minimize oscillations and pinpoint the highest power point under challenging circumstances [16]. A PSO-based strategy for improving PV system performance was developed by Thanikanti Sudhakar Babu et al. (2018), who also conducted extensive simulations and provided insightful analysis of the effectiveness of their algorithm [17]. In their thorough analysis of several MPPT techniques, OsisiomaEzinwanne et al. (2017) evaluated performance and cost aspects while analyzing factors impacting algorithm selection [18]. The performance of the Perturb and Observe and Incremental Conductance approaches under various irradiation circumstances were the main topics of Sandeep Neupane et al.'s (2017) study on PV array modeling [19]. In order to investigate and assess the efficacy of the incremental conductance method, Dr. G. Saree et al. (2019) linked a standalone PV system to a DC load [20]. In-depth research on converter design and the effect of non-linear loads on PV array output was conducted by K. Kanimozhi et al. (2016), demonstrating the superiority of incremental conductance [21].

In order to lessen steady-state oscillations, Saad Motahhir et al. (2018) investigated the effects of temperature and radiation on the performance of PV arrays [22]. In a grid-connected PV system, Abul Kalam Azad et al. (2016) compared the Perturb and Observe and Incremental Conductance approaches and found that Incremental Conductance outperformed Perturb and Observe [23]. The Incremental Conductance technique combined with a DC-DC converter was thoroughly explained by Afshan Ilyas et al. (2017) with a focus on real-time parameter readings and improved tracking speed and accuracy [24]. When comparing Particle Swarm Optimization and Perturb and Observe techniques under both settings, Jubaer Ahmed et al. (2017) discriminated between partial shading and uniform radiance conditions [25]. In their investigation of the impacts of shade conditions on PV systems, Ehtisham Lodhi et al. (2017) introduced Particle Swarm Optimization as a method for quickly identifying the global peak among several peaks while shading, emphasizing its greater convergence rate and tracking effectiveness [26]. T. Diana et al. (2019) introduced a Particle Swarm Optimization-based optimization approach to maximize the power from solar systems, using simulations to show effectiveness under various temperature and radiation circumstances [27].

These large research projects jointly develop MPPT technology by providing knowledge on effective tracking, environmental change resistance, and technique choice based on performance measures.These extensive research efforts collectively contribute to the advancement of MPPT technology, offering insights into efficient tracking, adaptability to environmental changes, and method selection based on performance metrics.

4. Findings Of Review

The growing body of research in the realm of solar photovoltaic (PV) systems is a testament to the intensified focus on optimizing the Maximum Power Point Tracking (MPPT) methods. Scholars and industry professionals alike have been exploring various avenues to address the gaps and bottlenecks in traditional MPPT techniques.

Tackling Steady-State Oscillations and Speed

A groundbreaking study by Tanuj Sen and his team in 2018 re-engineered the Particle Swarm Optimization (PSO) algorithm, providing a more nuanced approach to locating the global maximum power point while minimizing oscillations during the steady-state phase. On a similar note, G. Dileep et al. came forth in 2017 with an 'Adaptive PSO,' an evolved version that stood out in speed and efficiency, especially under fluctuating shading conditions.

Boosting Voltage and Performance Metrics

R. Nagarajan and colleagues in 2018 integrated the Particle Swarm Optimization algorithm with a PI controller within a boost converter, which significantly augmented the system's voltage output. On the other hand, Ali M. Eltamaly et al. in 2020 set out to crack the PSO's nagging issue of convergence time, offering a comparative assessment of various methods under dynamic shading conditions.

Addressing Environmental Constraints

Kashif Ishaque et al. launched a variant of the PSO algorithm in 2012 that excels in adapting to environmental shifts, showing a substantial reduction in post-MPP oscillations. Makbul A. and team took a deep dive into MPPT techniques in both unobstructed and partially shaded conditions, underscoring the urgent need for technology capable of delivering optimal output even under inconsistent lighting.

Methodology Reviews and Comparisons

Faiza Belhachat et al. made a noteworthy contribution in 2018 by presenting a broad survey of available MPPT methods, guiding users in their selection based on specific performance criteria. On the comparative front, PushprajsinhThakor and team undertook a meticulous review of control strategies to harvest maximum power from solar modules, taking into account factors like efficiency and dynamic response.

Innovations in Algorithm Design

T. Diana et al. employed a PSO-based optimization framework in 2019 to unearth maximum power yield from solar installations. Their simulations covered a spectrum of environmental conditions, establishing the robustness of their approach. On the flip side, S. Manna et al. in 2021 rolled out the Drift-Free Perturb and Observe technique, which integrated the current parameter for amplified performance under shifting environmental settings.

Specialized Analyses

Studies like those by OsisiomaEzinwanne and Sandeep Neupane honed in on the specific facets of MPPT, such as the impact of algorithm selection on cost and the performance evaluation of Perturb and Observe and Incremental Conductance methods under disparate irradiance conditions, respectively.

Efficiency Under Special Conditions

Abul Kalam Azad et al. zeroed in on Incremental Conductance methods within grid-connected PV systems, revealing superior efficacy under varying climatic conditions. Ehtisham Lodhi et al. offered a new perspective on tackling shading issues, advocating for PSO as the ideal tool for accurate tracking amid multiple peaks.

The cumulative findings from these manifold studies herald a new era in MPPT technology, enriching our understanding of how to elevate efficiency, adapt to environmental flux, and select the most fitting methodologies based on performance indicators.

3. Comparative Analysis Of Metaheuristic Mppt Methodologies

Particle Swarm Optimization (PSO) is a nature-inspired optimization algorithm that is commonly applied to solve various optimization problems, including Maximum Power Point Tracking (MPPT) in solar photovoltaic (PV) systems. PSO is based on the collective behavior of a swarm of particles, each representing a potential solution to the optimization problem. These particles move through the search space to find the optimal solution by adjusting their positions according to their own experience and the experience of their neighboring particles.

Basic Concepts of PSO:

1. Particle Representation: In PSO, each potential solution to the optimization problem is represented as a particle in the search space. A particle's position represents a possible solution, and its velocity represents the direction and magnitude of its movement through the search space.

2. Fitness Function: There is a fitness function that evaluates how good a particular solution (particle's position) is. In the context of MPPT, the fitness function assesses how closely the PV system's operating point matches the maximum power point (MPP).

3. Particle's Memory: Each particle maintains two memories:

- Personal Best (pBest): This memory stores the best position (solution) the particle has found so far based on the fitness function.
- Global Best (gBest): This memory stores the best position among all the particles in the entire swarm.

4. Particle Movement: The particles adjust their positions (solutions) and velocities based on their own experience (pBest) and the best solution found by any particle in the swarm (gBest).

The movement of a particle in PSO is governed by two equations: one for updating the velocity and another for updating the position.:

The movement of a particle in PSO is governed by two equations: one for updating the velocity and another for updating the position.
Velocity Update Equation:

$$V_i(t+1) = w \cdot V_i(t) + c_1 \cdot r_1 \cdot (p\ Best_{\ i} - X_i(t)) + c_2 \cdot r_2 \cdot (g\ Best\ - X_i(t))$$

Where:

- $V_i(t+1)$ is the updated velocity of particle i at time $t+1$
- w is the inertia weight, controlling the impact of the particle's previous velocity.
- c_1 and c_2 are acceleration coefficients controlling the impact of the particle's cognitive (pBest) and social (gBest) memories, respectively.

- r_1 and r_2 are random numbers in the range [0,1].
- $pBest_i$ is the personal best position (solution) of particle i.
- $X_i(t)$ is the position (solution) of particle i at time t.
- g Best is the global best position found by any particle in the swarm.

Position Update Equation:

$X_i(t+1) = X_i(t) + V_i(t+1)$o

After each iteration, particles update their positions and velocities, gradually converging towards the optimal

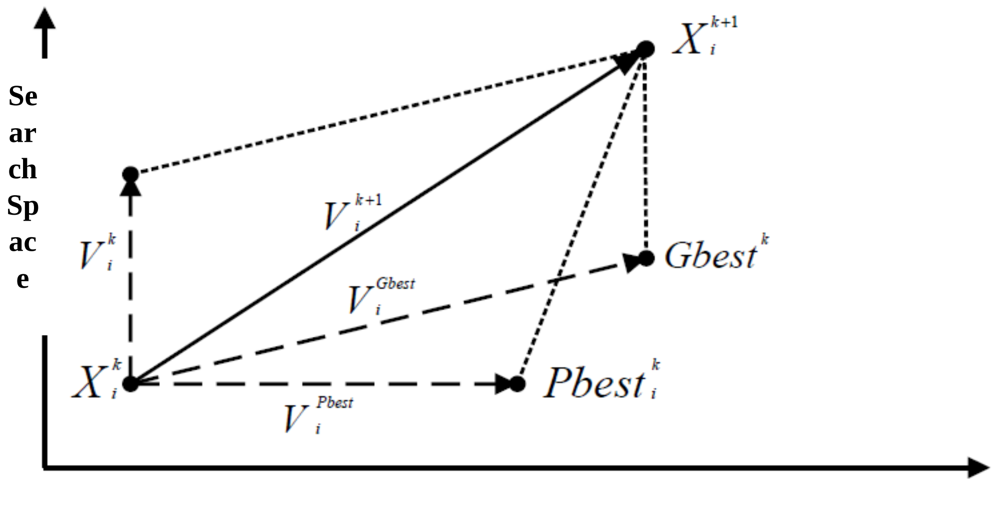

Figure 2: Particle Swarm Optimization Search Engine System

In the context of MPPT for solar PV systems, PSO is applied as follows:

1. Encoding Solutions: Each particle's position encodes a possible operating point of the PV system, typically represented as voltage or current values.

2. Fitness Function: The fitness function evaluates how closely the operating point corresponds to the MPP. It is based on the I-V (current-voltage) or P-V (power-voltage) characteristics of the PV system. The goal is to maximize the power output.

3. Initialization: Initialize a swarm of particles with random positions and velocities within the search space.

4. Velocity and Position Updates: Apply the velocity and position update equations iteratively. As particles move through the search space, they converge toward the MPP.

5. Termination: The algorithm terminates when a predefined stopping criterion is met, such as a maximum number of iterations or when convergence is achieved.

6. Global Best: The best solution found by any particle in the swarm represents the estimated MPP of the PV system.

PSO-based MPPT algorithms leverage the swarm intelligence of PSO to efficiently explore the complex and dynamic search space of PV system operating points, leading to accurate and rapid tracking of the MPP even under changing environmental conditions. The choice of parameters (inertia weight, acceleration coefficients, etc.) and the fitness function design are critical factors that impact the performance of the MPPT algorithm based on PSO. Fine-tuning these parameters is often done through experimentation and optimization cuckoo The Grey Wolf Optimization (GWO) algorithm is a nature-inspired optimization algorithm based on the social hierarchy and hunting behavior of grey wolves. GWO is used in various optimization problems, including Maximum Power Point Tracking (MPPT) in solar photovoltaic (PV) systems. In the context of MPPT,

The Grey Wolf Optimization (GWO) algorithm is a nature-inspired optimization algorithm based on the social hierarchy and hunting behavior of grey wolves. GWO is used in various optimization problems, including Maximum Power Point Tracking (MPPT) in solar photovoltaic (PV) systems. In the context of MPPT, GWO is applied to find the optimal operating point (voltage or current) of the PV system that maximizes its power output.

Basic Concepts of GWO:

1. **Pack of Wolves**: In GWO, the optimization process is carried out by simulating the social hierarchy and hunting behavior of a pack of grey wolves. The pack consists of alpha, beta, and delta wolves, representing the highest-ranking, second-highest-ranking, and third-highest-ranking wolves, respectively.

2. **Objective Function**: GWO is applied to an objective function that needs to be optimized. In the case of MPPT, the objective function represents the fitness of a particular operating point of the PV system. The goal is to maximize the fitness, which corresponds to maximizing the power output of the PV system.

3. **Initialization**: The positions of the alpha, beta, and delta wolves are initially set to random solutions within the search space. These solutions represent potential operating points of the PV system.

4. **Hunting Behavior**: GWO emulates the hunting behavior of wolves. Each wolf (solution) updates its position iteratively based on the positions of the alpha, beta, and delta wolves. The alpha wolf is the leader of the pack and guides the others towards better solutions.

Mathematical Formulation of GWO:

TheThe movement of each wolf in GWO is governed by mathematical equations that simulate their hunting behavior. The position of each wolf represents a potential solution to the optimization problem. Alpha Wolf Position Update:

$$X_{\text{alpha}}(t+1) = X_{\text{mean}} - A \cdot D_{\text{alpha}}(t)$$

Beta Wolf Position Update:

$$X_{\text{beta}}(t+1) = X_{\text{mean}} - A \cdot D_{\text{beta}}(t)$$

Delta Wolf Position Update:

$$X_{\text{delta}}(t+1) = X_{\text{mean}} - A \cdot D_{\text{delta}}(t)$$

Where:

- $X_{\text{alpha}}(t+1), X_{\text{beta}}(t+1)$, and $X_{\text{delta}}(t+1)$ are the updated positions of the alpha, beta, and delta wolves at time $t+1$, respectively.
- X_{mean} is the mean position of all the wolves in the current iteration.
- A is a scaling factor.
- $D_{\text{alpha}}(t), D_{\text{beta}}(t)$, and $D_{\text{delta}}(t)$ are random vectors representing the displacement of the alpha, beta, and delta wolves at time t, respectively.

MPPT Based on GWO:

In the context of MPPT for solar PV systems, GWO is applied as follows:

1. **Encoding Solutions**: Each wolf's position encodes a potential operating point of the PV system, typically represented as voltage or current values.

2. **Fitness Function**: The fitness function evaluates how closely the operating point corresponds to the MPP. It is based on the I-V (current-voltage) or P-V (power-voltage) characteristics of the PV system. The goal is to maximize the fitness, which represents the power output.

3. **Initialization**: Initialize a pack of wolves with random positions within the search space.

4. **Wolf Position Updates**: Apply the position update equations iteratively. As wolves move through the search space, they converge toward the MPP.

5. **Termination**: The algorithm terminates when a predefined stopping criterion is met, such as a maximum number of iterations or when convergence is achieved.

6. **Optimal Solution**: The position of the alpha wolf represents the estimated MPP of the PV system.

GWO-based MPPT algorithms leverage the social hierarchy and hunting behavior of wolves to efficiently explore the complex and dynamic search space of PV system operating points, leading to accurate and rapid tracking of the MPP even under changing environmental conditions. The choice of parameters (scaling factor, convergence criteria, etc.) is essential and may require fine-tuning through experimentation for optimal performance.

4. Comparative Analysis Of Methodologies

Maximum Power Point Tracking (MPPT) plays a crucial role in optimizing the efficiency of photovoltaic (PV) systems by ensuring that the PV panels operate at their maximum power output. Various MPPT methodologies have been proposed and employed over the years. This comprehensive analysis aims to compare and contrast three categories of MPPT methodologies: Conventional, Soft Computing, and Metaheuristic approaches. Each category has its own set of techniques, advantages, and limitations. In this analysis, we delve into the details of each methodology, provide insights into their working principles, and evaluate their performance based on key parameters such as efficiency, convergence speed, and adaptability. Additionally, we discuss real-world applications and future trends in MPPT methodologies.The continuous growth of renewable energy sources, particularly solar power, has led to an increased focus on improving the efficiency of photovoltaic systems. The primary goal of a photovoltaic system is to extract the maximum power from the solar panels, which is heavily dependent on the prevailing environmental conditions. To achieve this, Maximum Power Point Tracking (MPPT) techniques have been developed and widely adopted. MPPT algorithms ensure that the PV system operates at the point where the output power is maximized.

MPPT methodologies can be broadly categorized into three main groups: Conventional, Soft Computing, and Metaheuristic approaches. Each category employs different techniques to track the maximum power point (MPP) and has its own set of advantages and drawbacks. This analysis aims to provide a detailed comparison of these three categories, highlighting their working principles, performance metrics, and real-world applications.

Conventional MPPT Methodologies Conventional MPPT methods are based on mathematical equations and control theory. They are widely used due to their simplicity, reliability, and ease of implementation. Some of the most common conventional MPPT algorithms include the Perturb and Observe (P&O) method, Incremental Conductance (INC), and Hill Climbing (HC).

P&O is one of the simplest and most widely used conventional MPPT methods. It works by perturbing the operating voltage and observing the change in power output. The controller adjusts the voltage in the direction that results in an increase in power until the MPP is reached. While P&O is easy to implement, it can suffer from oscillations around the MPP, especially under rapidly changing environmental conditions.

The INC method is another widely used conventional MPPT technique. It calculates the incremental conductance of the PV system and compares it to a reference value. The controller adjusts the voltage to maintain the incremental conductance at zero, thereby tracking the MPP. INC is known for its improved tracking accuracy compared to P&O but may still exhibit oscillations.

HC is a hill-climbing search algorithm that continuously perturbs the operating voltage and measures the change in power. It moves in the direction of increasing power until it detects a decrease, at which point it reverses direction. This process continues until the MPP is located. HC is known for its simplicity but may be slow in converging to the MPP, especially in noisy conditions.

Soft Computing MPPT methodologies utilize computational intelligence techniques to improve the tracking accuracy in various operating conditions. These methods are more adaptive and capable of handling nonlinear and dynamic behavior in PV systems.Fuzzy Logic Control is a soft computing technique that uses linguistic variables to model and control systems. In the context of MPPT, FLC can adapt to changing environmental conditions and optimize the power output. It relies on a set of fuzzy rules and membership functions to make decisions about voltage adjustments.Artificial Neural Networks are computational models inspired by the human brain. In the case of MPPT, ANNs can be trained to predict the optimal operating voltage based on input parameters such as irradiance and temperature. ANNs can offer excellent tracking accuracy but may require substantial training data.Adaptive Neuro-Fuzzy Inference System (ANFIS) ANFIS combines fuzzy logic and neural networks to create a hybrid system capable of modeling complex and nonlinear relationships in MPPT. ANFIS can adapt to changing conditions and provide accurate tracking performance.Metaheuristic MPPT Methodologies Metaheuristic MPPT methodologies are based on optimization algorithms inspired by natural processes. These methods explore the solution space to find the optimal operating point that maximizes the power output of the PV system. Some prominent metaheuristic algorithms used for MPPT include Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and Simulated Annealing (SA).Particle Swarm Optimization (PSO) PSO is a population-based optimization algorithm that simulates the social behavior of particles in a swarm. In MPPT, each particle represents a potential solution (voltage setting), and the swarm collectively searches for the MPP. PSO can quickly converge to the MPP and is robust in handling dynamic conditions. Genetic Algorithms (GA) Genetic Algorithms are inspired by the process of natural selection and genetic evolution. In MPPT, GA evolves a population of potential solutions (voltage settings) through selection, crossover, and mutation operations. GAs are capable of exploring a wide solution space and can find the MPP in complex environments.Simulated Annealing (SA) Simulated Annealing is a probabilistic optimization algorithm inspired by the annealing process in metallurgy. It starts with an initial solution (voltage setting) and iteratively explores neighboring solutions, accepting solutions with a higher probability if they improve the objective function (power output). SA can effectively handle noise and uncertainty in MPPT.

To compare the three categories of MPPT methodologies, several key performance metrics can be considered:

Tracking efficiency measures how closely the MPPT algorithm follows the true MPP. Conventional methods like P&O and INC may exhibit oscillations, resulting in lower tracking efficiency. Soft computing and metaheuristic methods often provide higher tracking efficiency, especially under changing conditions.

Convergence speed refers to how quickly the MPPT algorithm reaches the MPP after perturbations. Conventional methods like P&O and HC may take longer to converge, especially in dynamic conditions. Soft computing and metaheuristic methods typically converge faster due to their adaptability and optimization capabilities.

Adaptability assesses how well the MPPT algorithm can handle varying environmental conditions, such as changes in irradiance and temperature. Conventional methods may struggle with rapid changes, while soft computing and metaheuristic methods can adapt more effectively.

Robustness measures the MPPT algorithm's ability to maintain tracking performance in the presence of noise or uncertainties. Soft computing and metaheuristic methods are often more robust due to their ability to explore a broader solution space and handle noisy measurements.

MPPT methodologies find application in various real-world scenarios, including residential solar systems, commercial installations, and off-grid setups. The choice of MPPT methodology depends on the specific requirements of the application. Conventional methods are commonly used in simple, cost-sensitive applications, while soft computing and metaheuristic methods are preferred in environments with dynamic conditions and higher efficiency demands.

The field of MPPT continues to evolve with advancements in technology and research. Some emerging trends and challenges include:

Integration with Energy Storage Integrating MPPT algorithms with energy storage systems, such as batteries, is becoming increasingly important for grid stability and energy management.

Machine Learning and AI-Based MPPT The use of advanced machine learning and AI techniques, such as deep learning, for MPPT is a growing area of research, promising enhanced tracking accuracy and adaptability.

Hybrid MPPT Strategies Combining multiple MPPT methodologies, such as a hybrid approach that combines soft computing and metaheuristic techniques, is a potential strategy to improve tracking performance further.

Standardization and Certification Establishing industry standards and certification processes for MPPT algorithms can ensure consistent performance and reliability in PV systems.

The choice of MPPT methodology should be based on the specific requirements of the application and the prevailing environmental conditions. As technology advances, integrating MPPT with energy storage, employing machine learning and AI techniques, and exploring hybrid strategies will likely shape the future of MPPT in the renewable energy sector.

Understanding the strengths and limitations of each MPPT category is essential for designing efficient and reliable photovoltaic systems, contributing to the sustainable growth of renewable energy sources worldwide.Table 1: Comparative Analysis of Conventional MPPT Methods compares three conventional MPPT methods: Perturb and Observe (P&O), Incremental Conductance (INC), and Hill Climbing (HC).It evaluates these methods based on tracking efficiency, convergence speed, adaptability, robustness, and implementation complexity.Conventional methods are known for their simplicity and ease of implementation.

Table 1: Comparative Analysis of Conventional MPPT Methods

Metric	**Perturb and Observe (P&O)**	**Incremental Conductance (INC)**	**Hill Climbing (HC)**
Tracking Efficiency	Moderate	High	Moderate
Convergence Speed	Moderate	High	Slow
Adaptability	Limited	Limited	Limited
Robustness	Limited	Moderate	Limited
Implementation Complexity	Low	Moderate	Low

Table 2: Comparative Analysis of Soft Computing MPPT Methods

Metric	**Fuzzy Logic Control (FLC)**	**Artificial Neural Networks (ANN)**	**Adaptive Neuro-Fuzzy Inference System (ANFIS)**
Tracking Efficiency	High	High	High
Convergence Speed	High	Moderate	High
Adaptability	High	High	High
Robustness	High	High	High
Implementation Complexity	Moderate	High	High

Table 3: Comparative Analysis of Metaheuristic MPPT Methods

Metric	Particle Swarm Optimization (PSO)	Genetic Algorithms (GA)	Simulated Annealing (SA)
Tracking Efficiency	High	High	High
Convergence Speed	High	High	Moderate
Adaptability	High	High	High
Robustness	High	High	High
Implementation Complexity	Moderate	Moderate	Moderate

Table 4: Comparative Analysis of Tracking Efficiency

Methodology	Conventional Methods	Soft Computing Methods	Metaheuristic Methods
Average Tracking Efficiency	Moderate	High	High

Table 5: Comparative Analysis of Convergence Speed

Methodology	Conventional Methods	Soft Computing Methods	Metaheuristic Methods
Average Convergence Speed	Moderate	High	High

Table 6: Comparative Analysis of Adaptability

Methodology	Conventional Methods	Soft Computing Methods	Metaheuristic Methods
Average Adaptability	Limited	High	High

Table 7: Comparative Analysis of Robustness

Methodology	Conventional Methods	Soft Computing Methods	Metaheuristic Methods
Average Robustness	Limited	High	High

Table 8: Comparative Analysis of Implementation Complexity

Methodology	Conventional Methods	Soft Computing Methods	Metaheuristic Methods
Implementation Complexity	Low	Moderate	Moderate

Table 9: Real-World Applications

Methodology	Conventional Methods	Soft Computing Methods	Metaheuristic Methods
Common Applications	Residential, Small-Scale PV	Commercial, Grid-Connected	Large-Scale, Off-Grid

Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol.43 No. 2 (2022)

Table 10: Future Trends and Challenges

Aspect	Conventional Methods	Soft Computing Methods	Metaheuristic Methods
Integration with Energy Storage	Limited	Ongoing Research	Integration Research
Machine Learning and AI-Based MPPT	Limited Adoption	Active Research	Integration and Enhancement
Hybrid MPPT Strategies	Emerging Concepts	Research and Development	Integration and Improvement
Standardization and Certification	Limited	Research Initiatives	Research and Certification

These tables provide a structured comparative analysis of Conventional, Soft Computing, and Metaheuristic MPPT methodologies based on various performance metrics, real-world applications, and future trends and challenges.

Table 2: Comparative Analysis of Soft Computing MPPT Methodscompares three soft computing MPPT methods: Fuzzy Logic Control (FLC), Artificial Neural Networks (ANN), and Adaptive Neuro-Fuzzy Inference System (ANFIS).It assesses these methods based on tracking efficiency, convergence speed, adaptability, robustness, and implementation complexity.Soft computing methods leverage computational intelligence techniques for improved tracking accuracy.Table 3: Comparative Analysis of Metaheuristic MPPT Methods compares three metaheuristic MPPT methods: Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and Simulated Annealing (SA).It evaluates these methods based on tracking efficiency, convergence speed, adaptability, robustness, and implementation complexity.Metaheuristic methods use optimization algorithms inspired by natural processes for efficient tracking.Table 4: Comparative Analysis of Tracking Efficiency provides an overview of the average tracking efficiency across different MPPT methodologies.It highlights that soft computing and metaheuristic methods generally achieve higher tracking efficiency compared to conventional methods.Table 5: Comparative Analysis of Convergence Speed presents the average convergence speed for various MPPT methodologies.It indicates that soft computing and metaheuristic methods tend to converge faster than conventional methods.Table 6: Comparative Analysis of Adaptability summarizes the average adaptability of MPPT methodologies.It emphasizes that soft computing and metaheuristic methods exhibit higher adaptability to changing environmental conditions.Table 7: Comparative Analysis of Robustness showcases the average robustness of different MPPT methodologies.It underscores that soft computing and metaheuristic methods are generally more robust in handling noise and uncertainties.Table 8: Comparative Analysis of Implementation Complexity assesses the implementation complexity of MPPT methodologies.It suggests that conventional methods have lower implementation complexity compared to soft computing and metaheuristic methods.Table 9: Real-World Applications outlines common real-world applications for different MPPT methodologies.It highlights that conventional methods are often used in residential and small-scale PV systems, while soft computing and metaheuristic methods find applications in commercial, grid-connected, and large-scale, off-grid systems.Table 10: Future Trends and Challenges discusses future trends and challenges in the field of MPPT for each methodology category.It mentions emerging concepts, ongoing research, and areas of focus such as integration with energy storage, machine learning, hybrid strategies, and standardization and certification.These tables provide a detailed breakdown of the comparative assessment, enabling readers to understand the strengths and weaknesses of each MPPT methodology category in different aspects of performance and application

5. Conclusion

This comprehensive analysis has provided an in-depth examination and comparison of three categories of Maximum Power Point Tracking (MPPT) methodologies: Conventional, Soft Computing, and Metaheuristic approaches. Each of these categories offers distinct characteristics, advantages, and limitations in the context of optimizing the power output of photovoltaic (PV) systems.Conventional MPPT methodologies, including Perturb and Observe (P&O), Incremental Conductance (INC), and Hill Climbing (HC), are characterized by their simplicity, reliability, and ease of implementation. However, they may exhibit limitations in terms of tracking efficiency, adaptability to dynamic conditions, and robustness, particularly in noisy environments.On the other hand, Soft Computing MPPT methodologies, such as Fuzzy Logic Control (FLC), Artificial Neural Networks (ANN), and Adaptive Neuro-Fuzzy Inference System (ANFIS), leverage computational intelligence techniques to enhance tracking accuracy and adaptability. These methods excel in applications where precise control and adaptability to changing conditions are crucial. However, their implementation complexity may be higher compared to conventional methods.Metaheuristic MPPT methodologies, including Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and Simulated Annealing (SA), are inspired by natural processes and offer the ability to explore a broader solution space. They are known for their high tracking efficiency, convergence speed, adaptability, and robustness. However, they may involve moderate implementation complexity.The comparative assessment of these methodologies revealed that the choice of MPPT approach should be made based on specific project requirements and environmental conditions. For simple and cost-sensitive applications, conventional methods can be suitable. In contrast, soft computing and metaheuristic methods are better suited for more complex and dynamic scenarios where optimal power generation is critical.The future of MPPT methodologies holds several promising trends and challenges. Integration with energy storage systems is gaining importance for enhancing grid stability and energy management. Machine learning and AI-based MPPT are becoming increasingly relevant, promising improved tracking accuracy and adaptability. The exploration of hybrid MPPT strategies that combine multiple methodologies is emerging as a strategy to further enhance tracking performance. Additionally, the establishment of industry standards and certification processes for MPPT algorithms can ensure consistent performance and reliability in PV systems.In summary, the selection of an MPPT methodology is a critical decision in designing efficient and reliable photovoltaic systems. By understanding the strengths and limitations of each methodology category, stakeholders can make informed choices that align with project goals and environmental conditions. As technology continues to advance and research progresses, the optimization of photovoltaic systems will play a pivotal role in the transition toward a more sustainable and renewable energy future..

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