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Maximum Power Point Tracking Techniques for Photovoltaic Systems: A Review

Narjis Nahedh Nadhim[1], Muhammed Sabri Salim[2*]

Authors affiliations:
1) Department of Electronics & Communication Engineering, College of Engineering, Al-Nahrain University, Jadriya, Baghdad, Iraq.
narjis.nahedh@gmail.com

2*) Department of Electronics & Communication Engineering, College of Engineering, Al-Nahrain University, Jadriya, Baghdad, Iraq.
mohammed.s.salim@nahrainuniv.edu.iq

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Abstract

Maximum Power Point Tracking (MPPT) techniques are essential for maximizing energy extraction from photovoltaic (PV) systems under diverse environmental conditions. This paper reviews three widely used MPPT methods Perturb and Observe (P&O), Fuzzy Logic Control (FLC), and Artificial Neural Networks (ANN) highlighting their effectiveness in addressing challenges such as temperature fluctuations, varying irradiance, and shading. The P&O method is noted for its simplicity and low computational requirements, but it suffers from oscillations around the maximum power point under rapidly changing conditions. FLC offers enhanced adaptability and robustness by mimicking human decision-making, performing well in dynamic environments with moderate complexity. ANN-based methods demonstrate superior tracking efficiency and fast convergence, particularly under complex and highly variable conditions, due to their ability to learn and generalize from data. These findings underscore the importance of continued development of MPPT techniques, especially intelligent and hybrid approaches, to meet the growing demand for sustainable energy. Thus, solar energy remains a highly viable solution for modern energy needs.

Keywords: MPPT, PV System, P&O, Fuzzy Logic, ANN, Solar Cell.

تقنيات تتبع نقطة القدرة القصوى للأنظمة الكهروضوئية: مراجعة

نرجس ناهض ناظم، محمد صبري سالم

الخلاصة:

تُعد تقنيات تتبع نقطة القدرة القصوى (MPPT) أساسيةً لتحقيق أقصى استفادة من الطاقة من أنظمة الطاقة الكهروضوئية في ظل ظروف بيئية متنوعة. تستعرض هذه الورقة البحثية ثلاث طرائق شائعة الاستخدام لتتبع نقطة القدرة القصوى (MPPT)، وهي: الاضطراب والمراقبة (P&O)، والتحكم المنطقي الضبابي (FLC)، والشبكات العصبية الاصطناعية (ANN)، مُسلِّطةً الضوء على فعاليتها في مواجهة تحديات مثل تقلبات درجات الحرارة، وتفاوت الإشعاع، والتظليل. تتميز طريقة P&O ببساطتها وقلة متطلباتها الحسابية، إلا أنها تعاني من تذبذبات حول نقطة القدرة القصوى في ظل ظروف سريعة التغير. يوفر التحكم المنطقي الضبابي (FLC) قدرةً مُحسَّنةً على التكيف والمتانة من خلال محاكاة عملية اتخاذ القرار البشري، ويؤدي أداءً جيدًا في بيئات ديناميكية متوسطة التعقيد. تُظهر الطرق القائمة على الشبكات العصبية الاصطناعية كفاءة تتبع فائقة وتقاربًا سريعًا، لا سيما في ظل ظروف معقدة وشديدة التغير، بفضل قدرتها على التعلم والتعميم من البيانات. تؤكد هذه النتائج على أهمية التطوير المستمر لتقنيات MPPT، وخاصةً المناهج الذكية والهجينة، لتلبية الطلب المتزايد على الطاقة المستدامة. وهكذا تظل الطاقة الشمسية تمثل حلاً قابلاً للتطبيق للغاية لتلبية احتياجات الطاقة الحديثة.

1. Introduction

Unquestionably, photovoltaic (PV) systems have become more and more important in the always changing terrain of renewable energy, fulfilling a wide spectrum of uses ranging from large-scale utility grids to distributed power solutions catered for residential homes and businesses, as well as addressing important remote power needs in many contexts. [1] The amazing increase in solar power applications may be mostly ascribed to important technological developments transforming the sector and increasing public and legislative knowledge of the many advantages solar energy provides. Beyond simple cost reductions, these advantages include lower energy prices, a significant drop in air pollution levels, and strong support of sustainable economic growth in all

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kinds of communities.[2] Adoption of solar photovoltaic energy has grown rapidly in recent years and has great potential to satisfy the always rising worldwide energy consumption that define contemporary society.[3] Currently on the market are several PV array technologies, each with unique characteristics and varied efficiency to meet various energy needs and preferences. [4] Although these technological developments have significantly raised energy conversion efficiency, boosting the power production from solar panels is still a continuous and vital goal the sector aims to reach.[5] Techniques including Maximum Power Point Tracking (MPPT) are vital tools in the efficient running of these systems since they help to establish and sustain ideal power output. [6] MPPT helps photovoltaic systems to find the ideal working point of solar panels, even under different environmental conditions, therefore enabling the highest possible power harvest from the sunlight accessible.[7] The complexity and difficulties in precisely identifying the Maximum Power Point (MPP), which is notably sensitive to important elements like temperature fluctuations, sunlight intensity variations, and shading effects from surrounding structures or foliage, highlight the value of MPPT.[8] Unlike conventional approaches, which might not always produce accurate results because of the erratic character of these environmental factors, MPPT techniques offer greatly more efficient and dependable solutions. [9] These creative ideas fall into multiple frameworks: classical optimization techniques, fuzzy logic applied with artificial intelligence, and the use of advanced neural networks. [10] The need of renewable energy keeps growing fast, therefore the function and relevance of MPPT in photovoltaic systems become more important and crucial to guarantee that solar power technology can contribute significantly and practically to a sustainable energy future for all. [11]

2. MPPT

Maximum Power Point Tracking (MPPT) is an important and necessary method used in photovoltaic (PV) systems that helps very much to get the most power out of solar panels. Solar panels' power and current can change a lot as the sun moves around during the day. This means that their overall efficiency and performance are affected. [12] This problem is solved by using clever MPPT methods to make sure that the PV system makes the most of the power that is available at any given time. [13]

While changing the inverter's working point at the same time, the MPPT mechanism is meant to keep an eye on the PV array's output voltage and current. Keeping the performance level you want relies on this dynamic change. Figure 1 shows how the MPPT method is supposed to work. MPPT technology makes solar energy systems work much better by finding the Maximum Power Point (MPP), which is the exact point where the product of current and voltage is greatest. [14]

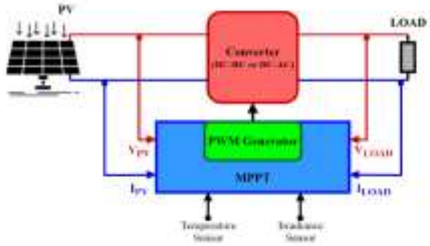

Figure (1): Operating scheme of the MPPT system.[5]

Usually involving a DC-DC converter, this procedure deftly modulates the voltage to match the voltage level at which the array runs most effectively. [15] This clever adaption finally converts solar energy into useable electricity, so enabling several uses. Basically, MPPT guarantees that PV systems run at maximum efficiency and helps them to reach a better degree of productivity independent of the different climatic conditions seen during the day. [16] This essential feature makes MPPT a must-have tool for optimizing energy output in solar power plants, therefore guaranteeing that the solar technology investment pays out the best returns.[17], [18]

3. Classification of MPPT techniques

Three widely accepted approaches for Maximum Power Point Tracking (MPPT) are the subject of continuous discussion and development: artificial neural networks (ANN), fuzzy logic control (FLC), and perturb and observe (P&O). Each of these techniques offers a unique strategy for optimizing energy extraction in photovoltaic (PV) systems. P&O is appreciated for its simplicity and ease of implementation, FLC offers flexibility and adaptability to varying environmental conditions, and ANN excels at handling complex and nonlinear data patterns for high-accuracy tracking. While several other MPPT methods exist such as Incremental Conductance (IncCond), Fractional Open Circuit Voltage (VOC), Fractional Short Circuit Current (ISC), and hybrid MPPT strategies this review focuses specifically on ANN, FLC, and P&O due to their widespread use, diversity in design principles, and strong representation across both academic research and industrial applications. These three techniques highlight distinct paradigms classical, rule-based, and AI-driven that are central to understanding the evolution and future of MPPT technologies in renewable energy systems.

3.1. Perturb and Observe (P&O) Algorithm

In this technique, the voltage is subjected to a disturbance, and the subsequent change in power is observed. If the power is greater, the voltage must be increased to obtain the maximum power, and vice versa. Accordingly, in P&O, a small step change in voltage (perturbation) is affected, and the new power is observed.[19] Based on the comparison of the power data obtained in each iteration, a decision about the direction of search is taken. By repeating this process, the maximum power operating point is ultimately reached.[20] The principle of operation of the perturb and observe algorithm is based on the observation made on a P-V characteristic. Fig. 2 show

Conventional flowchart of P&O method. The observation is that when a voltage beyond Vγ is present across the PV cell array, it delivers drastically low power and draws unnecessary array current, thereby causing a power loss.[21]

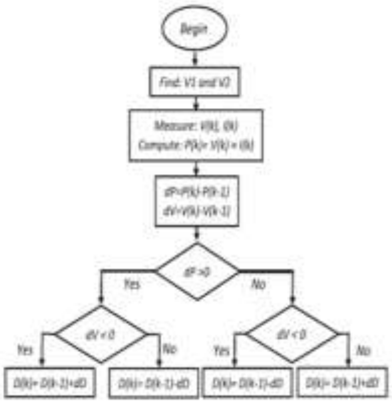

Figure (2): Conventional flowchart of P&O method.[22]

The Perturb and Observe (P&O) MPPT algorithm begins by initializing two voltage values, V1 and V2. It then measures the instantaneous voltage V(k) and current I(k) to calculate power $P(k) = V(k) \times I(k)$. The changes in power (ΔP) and voltage (ΔV) are computed between successive samples. If $\Delta P > 0$ and $\Delta V < 0$, the duty cycle D(k) is decreased; otherwise, it is increased. If $\Delta P < 0$, D(k) is increased for $\Delta V < 0$, and decreased otherwise, adjusting the operating point accordingly. As shown in figure 2.

The power preparedness can be raised by either adjusting the array iterative voltage or by increasing γ. On the other hand, operating at the MPP involves little power loss due to its dynamic nature.[23] This P&O algorithm is based on the assumption that under steady-state sunlight conditions, the power output from the PV array always varies monotonically with respect to the array voltage around its maximum power point. Therefore, under steady-state conditions, the instantaneous change in output power associated with a change in output voltage or current will change monotonically to their updated values.[22] If these changes do not result in the desired condition, the voltage and/or current will continue to increase or decrease in the same direction to arrive at the maximum value of power at the maximum power point.

The Perturb & Observe (P & O) method has notable strengths and weaknesses. Among its strengths, P & O is characterized by its simplicity and ease of implementation, allowing for broad applicability with minimal computational resource requirements, which enhances accessibility.[21] Its cost-effective character also usually results in cheaper deployment costs because of less hardware need. Moreover, P & O is able to react fast to changes in environmental circumstances, hence optimizing the output of solar panels. [24] Its great use also suggests that users have easy access to plenty of research. This method has flaws as well, including a tendency to oscillate about the maximum power point under quickly changing conditions, which can lead to power losses. [22] [25] It is extremely sensitive to noise, which could lead to erroneous tracking of the greatest power point under changing conditions especially. Furthermore, P & O may suffer in settings with dynamic solar fluctuations, partial shading, and occasionally it may take more time to converge to the maximum power point, therefore producing temporary inefficiencies in power collecting. [26] Although the P & O MPPT method provides good advantages generally, its oscillation, noise sensitivity, and performance limitations under various settings point up areas that require development. [24]

Manoharan et al. 2021 [27], For more exact tracking of the maximum power point (MPP), the suggested methodology in this work offers an Adaptive Perturb and Observation (AMP&O) strategy that combines changes in current alongside the conventional changes in voltage and power. Using MATLAB/Simulink and laboratory investigations, the proposed methods were validated under several conditions, including abrupt changes in insolation, by means of simulations. Results showed a tracking efficiency of over 95% with greatly lowered power oscillations and shorter convergence times, so demonstrating the accuracy of the AMP&O technique in tracking the MPP even under fast changing environmental conditions and so verifying its simplicity and robustness for useful applications in solar power.

3.2. Fuzzy Logic Control (FLC)

Mostly applied in renewable energy systems, particularly in photovoltaic (PV) solar panels, fuzzy logic control (FLC)-based Maximum electricity Point Tracking (MPPT) is a creative and effective way used to properly collect power. [28] This creative solution deftly manages the inherent uncertainty and the nonlinear properties connected with the generation of solar power by using fuzzy logic ideas. FLC essentially runs by copying human rational thinking and decision-making, thereby enabling it to make informed decisions depending on inaccurate input factors. [29] In the framework of MPPT, it actively analyzes the dynamic and changing conditions of solar irradiation and temperature, thereby allowing it to ascertain, in real-time, the best working point of a solar panel. [30]

The controller maximizes power production with amazing efficiency by processing essential inputs including voltage and current using a well crafted set of fuzzy rules, so making required modifications to the operating point. Figure 3 displays FLC construction for MPPT. One of the main benefits of FLC-based MPPT is its great adaptation to different environmental circumstances, which can often be erratic and great resilience. [31]

In figure 3 (FLC) based MPPT algorithm starts by measuring the PV output voltage V(k) and current I(k) to compute power $P(k) = V(k) \times I(k)$. It then calculates the error E(k) as the slope of the P-V curve and the change in error $\Delta E(k)$. These values are fuzzified into linguistic terms, which are processed by the inference engine using a rule base. Finally, the fuzzy output is defuzzified into a precise control action to adjust the duty cycle D for optimal power tracking.

Under fast changing situations, traditional MPPT methods as the Perturb and Observe (P&O) approach or the Incremental Conductance (IncCond) technique might sometimes find it difficult to keep pace. [32], [33] By means of fuzzy logic control, on the other hand, one may efficiently handle such fluctuations and guarantee that the system always stays at or close to the maximum power point, hence optimizing energy output. [34] Moreover, FLC is rather easier to use and integrate since it does not depend on extremely exact mathematical models of the system itself. It can be made to efficiently combine insightful expert information and ideas, therefore enabling a great degree of customizing that would result in better performance in certain uses. [35] [36] FLC-based MPPT is especially attractive for improving the dependability and efficiency of solar energy systems because of this adaptability and capacity to manage different uncertainty. [37] Fuzzy Logic Control really offers a creative and efficient way for the successful application of Maximum Power Point Tracking, greatly increasing the energy yield of solar power systems and gently allowing different operating conditions and inherent complexity related with solar energy generating technology. [38]

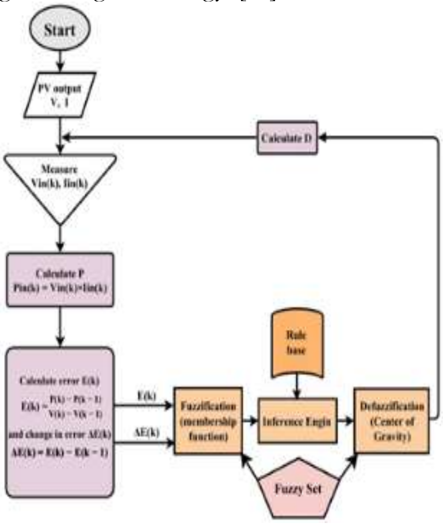

Figure (3): Construction of FLC for MPPT.[31]

Baramadeh et al. 2021 [31] prepares a project aims to design and implement a Maximum Power Point Tracker (MPPT) for photovoltaic (PV) systems using a Fuzzy Logic Control (FLC) technique—more especially, with an eye on performance with a battery load instead of a normal resistive load. Simulating in MATLAB/Simulink, the MPPT system lowers oscillations and settling periods to maximize power extraction from the PV array, hence extending battery life. Environmental factors are examined. The FLC technique efficiently controlled the non-linear features of the PV system, so showcasing outstanding performance in tracking the highest power point based on simulation results indicating effective power generating even under diverse solar irradiation and temperature conditions. The results showed an incredible degree of efficiency, thereby demonstrating in real-time operations the adaptability and robustness of the system.

3.3. Neural Network-based MPPT

Increasingly used in photovoltaic systems to maximize the extraction of solar energy in the most effective manner, neural network-based Maximum Power Point Tracking (MPPT) is a novel and advanced approach. This novel approach forecasts the ideal operating point of a solar panel by using artificial neural networks (ANNs), computer models derived from the human brain. [39] By doing this, one considers many environmental factors including voltage variations, solar irradiation, and temperature.

Harnessing neural networks for MPPT has a basic benefit in their amazing capacity to learn from past data, which makes them rather effective in adjusting to fast changing situations occurring in real-time. [40] Neural networks have the special ability to generalize from past events unlike conventional MPPT systems, which can rely on predefined mathematical models with limited flexibility. [41] This feature enables them to constantly enhance their tracking performance over time, thereby producing much higher energy yields, especially in non-uniform light situations or under changing environmental conditions that are typical in solar collecting. [42] An extensive training dataset is needed to properly apply a neural network-based MPPT system. Usually including several input variables, such temperature fluctuations and irradiation levels, this dataset also has expected outputs showing the maximum power points under different conditions. [43] By means of a methodical training process, the neural network gains knowledge of the complex interactions among these inputs and outputs. This learning helps the network to dynamically and effectively estimate the ideal operating point in real-time, hence improving the system. [44]

Figure 4 provides an ANN algorithm flowchart. This method improves not only the energy extraction efficiency from solar systems but also the lifetime and durability of the whole system. [45] [46] It guarantees that the photovoltaic system may run efficiently for a longer period by always optimizing the operating conditions and reducing stress on the components. [47], [48] Consequently, including neural network-based MPPT approaches into solar energy systems marks a major advancement in renewable energy technology and opens the path for more intelligent and effective solar power solutions. [49] [50]

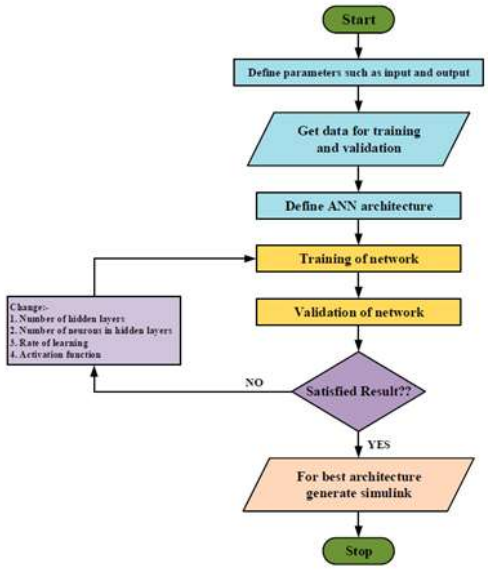

Figure (4): Flowchart of ANN Algorithm.[43]

ANN-based MPPT uses input data such as irradiance and temperature to predict the MPP voltage or current. It learns from a training dataset and adjusts weights during the training process using algorithms like Levenberg–Marquardt or BFGS.

Hussain et al. 2023 [43] evaluates and compares six artificial neural networks (ANN) algorithms—Levenberg–Marquardt (LM), Bayesian regularization (BR), resilient backpropagation (RP), gradient descent momentum (GDM), Broyden–Fletcher–Goldfarb–Shanno (BFGS), and scaled conjugate gradient (SCG)—for maximum power point tracking (MPPT) energy harvesting in solar photovoltaic (PV) systems. Using a dataset of solar irradiation, temperature, and voltage, the implementation developed models within MATLAB or Simulink separated into training, validation, and testing sets for the ANN. While RP and BR also showed good performance, results revealed that compared to the others, the LM and BFGS algorithms displayed better performance metrics including gradients and regression values. The fact that SCG and GDM were found to be less efficient generally emphasizes the need of algorithm choice in maximizing energy collecting efficiency.

Table (1): Mppt Techniques - Previous Work Done

Authors	MPPT technique	Results
Karthika et al. 2020 [19]	Enhanced P&O	effectively reduces steady-state oscillations and response time, achieving maximum power points between 60% and 80% of open-circuit voltage, validated through simulations and practical tests.
Lodin Afghanistan 2019 [22]	Predictive-P&O	predictive-P&O MPPT algorithm demonstrates enhanced power stability and reduced oscillations, achieving faster convergence to the maximum power point compared to traditional P&O methods in solar energy systems.
Manoharan et al. 2021 [27]	Improved P&O	Attained over 95% tracking efficiency, decreased power oscillations, and guaranteed precise maximum power point tracking during rapid insolation fluctuations, surpassing conventional approaches in both simulation and experimental outcomes.
Ali et al. 2021 [30]	fuzzy logic-based variable-step incremental conductance	enhances tracking efficiency, improves output DC power, and reduces convergence time under changing environmental conditions compared to traditional methods.
Baramadeh et al. 2021 [31]	Fuzzy Logic Contro	The simulation results indicated that the Fuzzy Logic Control MPPT effectively optimized power production from the PV system with a battery load, attaining minimal settling time and diminished oscillations, hence improving battery lifespan.
Li et al. 2019 [28]	Beta Parameter Based Fuzzy-Logic Controller	Exhibited enhanced tracking efficiency, accelerated convergence speed, and eradicated oscillations around maximum power points under fluctuating solar irradiation circumstances in contrast to conventional maximum power point tracking methods.
YILMAZ et al. 2022 [49]	ANN	shown enhanced efficiency, settling time, and overshoot relative to conventional P&O and INC algorithms, guaranteeing excellent functionality under fluctuating irradiance and temperature circumstances.
Hussain et al. 2023 [43]	ANN	The findings demonstrate that the LM and BFGS algorithms outperform in MPPT performance, exhibiting optimal regression values and gradients, whereas the RP and BR algorithms get quicker convergence but exhibit reduced overall accuracy.
Gündoğdu et al. 2020 [40]	ANN	Exhibited enhanced performance in optimizing maximum power under fluctuating situations, attaining greater efficiency and reduced power ripple relative to traditional Perturb & Observe and incremental conductance techniques.

Table (2): Comparative Analysis of MPPT Techniques

Technique	Tracking Efficiency	Convergence Time	Complexity	Implementation Cost	Robustness to Environment	Advantages	Disadvantages
Perturb & Observe (P&O)	Moderate	Moderate	Low	Low	Low (sensitive to rapid changes)	Simple to implement, cost-effective, widely studied	Oscillations around MPP, poor performance under fast-changing conditions, fixed step size limits accuracy

Fuzzy Logic Control (FLC)	High	Fast	Medium	Medium	High (adaptive to changes)	Adaptive to environmental changes, no need for precise model, smooth response	Rule design requires expert knowledge, tuning is application-specific, moderate computational needs
Artificial Neural Network (ANN)	Very High	Very Fast	High	High	Very High (learns patterns)	Learns from data, fast and accurate tracking, handles nonlinearity well	Requires large training data, high implementation cost, complexity in training and deployment

While MPPT techniques offer significant improvements in energy harvesting from PV systems, each method presents unique challenges in practical implementation: Perturb and Observe (P&O): Despite its simplicity and low computational cost, P&O suffers from persistent oscillations around the maximum power point, especially under rapidly changing irradiance. This can lead to energy losses and system instability. Additionally, its fixed step size often forces a trade-off between speed and accuracy. Fuzzy Logic Control (FLC): FLC performs well under dynamic conditions, but it requires extensive rule-based system design, which is often based on expert intuition rather than a universal model. This can complicate its tuning and limit scalability across different PV configurations or environmental settings. Artificial Neural Networks (ANN): ANN-based MPPT provides high accuracy and fast response, but it demands significant computational resources for training and real-time processing. Its dependence on high-quality datasets and potential overfitting to specific conditions can reduce adaptability unless the model is periodically retrained. These implementation constraints must be considered when selecting or designing MPPT strategies for real-world PV applications, particularly for embedded or low-cost systems.

4. Conclusion

As global demand for renewable energy intensifies, Maximum Power Point Tracking (MPPT) techniques play a vital role in improving the efficiency and reliability of photovoltaic (PV) systems. This review examined three widely adopted MPPT methods—Perturb and Observe (P&O), Fuzzy Logic Control (FLC), and Artificial Neural Networks (ANN)—each with distinct operational characteristics. P&O stands out for its simplicity, low implementation cost, and widespread use, but it suffers from instability and reduced performance under rapidly changing environmental conditions due to its reliance on iterative perturbations. FLC offers greater adaptability and robustness, using human-like reasoning through fuzzy rules to handle non-linear system behavior effectively. However, its performance depends heavily on well-crafted rule sets, which can limit scalability and require expert tuning. ANN-based techniques deliver the highest tracking accuracy and rapid convergence, particularly under variable irradiance and temperature. Yet, their implementation is computationally intensive and depends on the availability of extensive training datasets. While each method contributes uniquely to MPPT optimization, several research gaps remain. Future efforts should focus on real-time embedded implementation for low-power and remote systems, the development and field validation of hybrid MPPT strategies (e.g., Fuzzy-ANN, P&O-ANN), and integration with energy storage systems for comprehensive power management. Additionally, the emergence of self-adaptive, data-driven MPPT systems capable of learning and evolving with operational data presents a promising frontier. Addressing these challenges will be essential to developing intelligent, resilient, and efficient solar energy solutions that can support a scalable and sustainable global energy transition.

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