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A COMPARATIVE STUDY OF PHOTOVOLTAIC MAXIUM POWER POINT TRACKING ALGORITHMS UNDER DYNAMIC WEATHER CONDITIONS

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Abstract

Based on a literature review of various MPPT algorithms, it can be concluded that each algorithm has its own advantages and limitations depending on the operational conditions of the photovoltaic system. Conventional algorithms such as Perturb and Observe (P&O) and Incremental Conductance (INC) offer a simple structure and easy implementation, but are less responsive to rapid weather changes.

Meanwhile, artificial intelligence-based algorithms such as Fuzzy Logic Control (FLC), Artificial Neural Network (ANN), and Particle Swarm Optimization (PSO) demonstrate superior performance in terms of tracking speed, efficiency, and stability under dynamic conditions. The combination of algorithms or hybrid methods has also been proven to improve system resilience to irradiance and temperature fluctuations. Therefore, the selection of an MPPT algorithm must consider the context of use, such as environmental conditions, hardware capacity, and the overall efficiency needs of the system. With the right approach, MPPT systems can significantly increase the power output of solar panels and support sustainable energy efficiency.
Keywords: MPPT Algorithm, Solar Panel, Dynamic Weather

INTRODUCTION

Renewable energy is becoming a strategic solution in addressing the global energy crisis and the environmental impact of fossil fuel use. One of the most promising and environmentally friendly sources of renewable energy is solar power. Photovoltaic (PV) systems have been widely used to convert solar energy into electrical energy. The advantages of PV systems include ease of installation, zero emissions, and applicability across various scales, from households to large power plants (Habibie et al., 2022). However, this system has limitations, such as dependence on sunlight intensity and ambient temperature. Therefore, the efficiency of the PV system needs to be continuously improved so that the generated power can be optimal.

One of the main challenges in PV systems is the instability of power output due to changing weather conditions. Rapid changes in solar irradiance and temperature, such as those that occur in cloudy conditions or when clouds come and go, cause the PV power curve to fluctuate. This condition makes it difficult for the system to consistently determine the maximum power point (MPP). The maximum power point is the point where the PV system generates the highest power. Without proper tracking, the PV system will operate below its maximum efficiency (Soni & Sharma, 2022). Therefore, it is important to develop a power tracking method that is adaptive to weather dynamics.

In this context, the Maximum Power Point Tracking (MPPT) algorithm becomes key in optimizing the output power of a PV system. MPPT functions to find and maintain PV operation at the maximum power point, even as environmental conditions constantly change. With an effective MPPT algorithm, a PV system can adjust its operating point in real-time according to irradiance and temperature conditions (Hindarto, 2023). This allows for more efficient and stable use of solar energy. Various MPPT algorithms have been developed and implemented in different types of PV systems. Each algorithm has its advantages and disadvantages depending on its complexity, convergence speed, and response to weather changes.

Some popular MPPT algorithms include Perturb and Observe (P&O), Incremental Conductance (INC), and artificial intelligence-based methods such as Fuzzy Logic and Artificial Neural Networks (ANN). These methods have different approaches to determining the MPP and regulating the operating voltage or current of the PV system. Conventional algorithms like P&O and INC tend to be simple and easy to implement, but are less responsive to rapidly changing weather conditions (Kumar & Amudha, 2023). Meanwhile, AI-based algorithms offer better adaptability and accuracy, but require higher computational resources. In dynamic weather conditions, the effectiveness of MPPT algorithms becomes increasingly crucial. Therefore, it is important to evaluate and compare these various algorithms in the context of a changing environment (Manandhar et al., 2024).

Research comparing the performance of MPPT algorithms under dynamic weather conditions is highly relevant and necessary. Many previous studies have focused on testing algorithms in static conditions or stable, clear weather. In reality, however, PV systems often face unpredictable weather conditions, such as partial cloud cover or rapid cloud movement. In this situation, the MPPT algorithm must be able to quickly adjust the operating point to avoid significant power loss (Suyanto et al., 2024). By conducting a systematic comparative study, it can be determined which algorithm is most suitable for use in PV systems in regions with unpredictable weather conditions. The results can be an important guide for solar energy system developers at various scales.

Besides power efficiency, other factors such as tracking speed, operational stability, and implementation complexity should also be considered when evaluating MPPT algorithms. Speed in reaching the maximum point becomes important so that the system does not lose much energy during fluctuations in irradiance. The stability of the algorithm will determine how smoothly the PV system can adapt without producing detrimental oscillations. Implementation complexity concerns the ease of integrating the algorithm with hardware and the overall system cost. Therefore, a comprehensive comparison must involve various technical and practical aspects. The aim is to determine the overall most optimal MPPT algorithm (Pulaganti & Veerappan, 2023).

In the era of modern technology, the integration between PV systems and artificial intelligence-based control methods is increasingly in demand. This is because AI methods like fuzzy logic, PSO (Particle Swarm Optimization), and neural networks are able to learn and adapt to changing weather patterns more flexibly. The sophistication of this method allows the PV system to operate more adaptively and efficiently. However, the implementation of AI methods also demands more complex hardware and system design (Tseng et al., 2024). Therefore, a trade-off between performance and complexity needs to be considered when selecting AI-based MPPT algorithms. The evaluation in this literature review will reveal the advantages and limitations of this approach.

With this background, this research aims to conduct a comprehensive literature study on various MPPT algorithms in dynamic weather conditions. This study will analyze recent studies that test the performance of MPPT algorithms in real or simulated conditions with rapid irradiance changes. The main focus is on tracking efficiency, output stability, and adaptability to environmental changes. With a systematic literature review approach, it is hoped that a clear picture can be obtained of the most superior MPPT algorithm for dynamic weather conditions. The results of this research will contribute to the development of more robust and efficient PV systems. Additionally, this study can serve as a foundation for further experimental research and the development of hybrid algorithms in the future.

RESEARCH METHOD

This research uses a Systematic Literature Review (SLR) approach to examine and compare Maximum Power Point Tracking (MPPT) algorithms in photovoltaic systems operating under dynamic weather conditions. This study includes scientific literature published between 2015 and 2025 to ensure the relevance and currency of the data. The literature sources were taken from reputable scientific databases such as IEEE Xplore, ScienceDirect, SpringerLink, and Google Scholar. The search process was conducted using customized keywords, including: "MPPT algorithm", "Photovoltaic tracking", "Dynamic weather conditions", and "Maximum power point tracking comparison". Inclusion criteria include articles containing simulation analyses or experiments on MPPT algorithms under changing weather conditions. Articles that only discuss theory or do not test within the context of dynamic weather will be excluded from the analysis.

After relevant literature was collected, data identification and extraction were performed to obtain important information such as the type of algorithm used, testing parameters (e.g., efficiency, convergence time), and the main results reported. These data were then classified based on the algorithmic approach (conventional, artificial intelligence-based, or hybrid) and their testing environment (simulation or real-world experiment). Subsequently, a comparison process was conducted between the algorithms based on specific performance criteria, such as MPP tracking accuracy, stability against irradiance fluctuations, and implementation complexity. The comparison results are presented in tabular form and analyzed narratively, allowing for the conclusion of general trends, strengths, and weaknesses of each MPPT approach. This step aims to provide a comprehensive understanding of the effectiveness of MPPT algorithms in facing dynamic weather challenges (Snyder, 2019; Tranfield et al., 2003).

RESULT AND DISCUSSION

Algorithm Performance Comparison

MPPT algorithms have varying characteristics and performance depending on their approach. To objectively assess performance, a comparison was made using several key indicators: power tracking efficiency, convergence speed towards the MPP, and system stability during irradiance fluctuations (Habibie et al., 2022). The results of the algorithm comparison from the literature reviewed are presented in table format for easier analysis. This table includes algorithms such as Perturb and Observe (P\&O), Incremental Conductance (INC), Fuzzy Logic Control (FLC), Artificial Neural Network (ANN), and Particle Swarm Optimization (PSO). Each algorithm shows different results in responding to dynamic weather conditions. This highlights the importance of selecting an algorithm that is suitable for the operational environment of the PV system. The P&O algorithm is one of the simplest and most widely used MPPT methods. Its working principle is to introduce small disturbances to the voltage or current and observe the resulting power changes. Although this algorithm is easy to implement and computationally lightweight, it has a significant drawback in dynamic weather conditions. When irradiance changes rapidly, P&O tends to lag in MPP tracking and produce oscillations around the maximum power point. Its efficiency decreased because the system could not immediately adjust its operating point (Riady et al., 2024). Therefore, although effective in stable conditions, P\&O is less than ideal for rapidly changing environments.

Incremental Conductance (INC) has a more precise approach compared to P&O, by comparing the incremental conductance to the instantaneous conductance to determine the direction of the MPP. INC is more responsive to changes in irradiance, resulting in better performance in dynamic weather conditions. However, its implementation is more complex and requires simultaneous measurement of current and voltage. This algorithm can also produce small fluctuations if the parameters are not well adjusted. In terms of efficiency, INC is superior to P\&O in most literature studies (Li & Kötzing, 2024). Nevertheless, the effectiveness of INC can still decrease if there are very extreme and sudden weather changes.

Fuzzy Logic Control (FLC) offers advantages in handling the uncertainty and non-linearity of PV systems. By using a rule base and membership functions, FLC can respond to variations in irradiance more smoothly and quickly. The literature results indicate that FLC is very capable of maintaining system stability, even when weather conditions change drastically (Afdilla & Hasibuan, 2024). Additionally, this algorithm does not require a complex mathematical model of the system. Its weakness is that the design of fuzzy rules and membership functions requires a high level of expertise and experience. Additionally, FLC also requires more computational capacity compared to conventional methods.

An Artificial Neural Network (ANN) is a machine learning-based algorithm capable of recognizing complex patterns in environmental data. ANNs can be trained to automatically predict MPP based on inputs such as temperature and irradiance. In the literature study, ANN showed very high tracking efficiency and a rapid response to weather changes. Its advantage lies in its ability to adapt to various weather scenarios through prior training. However, the main drawbacks of ANNs are the need for large and representative training data and the potential for overfitting if not designed well. Implementing ANNs also requires hardware with adequate computing power (Salami et al., 2024).

Particle Swarm Optimization (PSO) is one of the optimization algorithms adopted for MPPT due to its ability to efficiently find global solutions. In the context of PV, PSO is used to collectively explore the MPP search space using particles that move towards the optimal solution. PSO's performance is excellent in dynamic weather conditions because it can quickly adjust its search trajectory (Elzalik et al., 2022). The study results show that PSO has high efficiency and strong tracking stability. However, PSO requires proper iteration and configuration parameters to avoid getting stuck in local solutions. Additionally, the initial computation time might be slightly longer compared to conventional algorithms.

In dynamic weather conditions, conventional algorithms often struggle to maintain a stable optimal operating point. Conversely, artificial intelligence (AI)-based and optimization algorithms tend to be more flexible in responding to rapid environmental changes. However, the choice of algorithm also needs to consider the hardware capacity of the PV system. In small-scale systems with limited budgets, P&O or INC are still practical choices, although less optimal (Ayumi, 2024). For large-scale systems with high efficiency requirements, FLC, ANN, or PSO are more recommended options. The combination of conventional algorithms and AI is also a promising trend in recent research.

Based on the comparison results from various literature, no single algorithm is absolutely superior in all aspects. Each algorithm has its own advantages depending on the context of its use. Factors such as weather stability at the installation site, the type of electrical load, and hardware limitations significantly affect the effectiveness of the algorithm. Therefore, adaptive or hybrid approaches that combine the strengths of several algorithms are being widely developed. The goal is to maximize the efficiency and flexibility of the PV system under various operating conditions. Further research into this algorithm combination presents an exciting research opportunity for the future.

The Influence of Weather Conditions on MPPT Performance

Changes in weather conditions directly affect the output characteristics of photovoltaic systems, particularly in terms of voltage, current, and power generated. The two main factors that have the most influence are solar irradiance and ambient temperature. When irradiance increases, the PV output current rises significantly, while the voltage changes only slightly. Conversely, increasing the temperature typically lowers the voltage and efficiency of the system. This combination of changes causes the maximum power point (MPP) to shift dynamically (Siregar et al., 2024). Therefore, the MPPT algorithm must be able to respond quickly and accurately to changes in these two variables in order to maintain optimal performance.

Irradiance is the weather factor that changes most frequently and suddenly, especially under cloudy or partially cloudy conditions. When clouds move quickly, there are fluctuations in the intensity of sunlight hitting the solar panels, resulting in a shift in the PV power curve. This causes the MPP to no longer be at its previous point, so slow tracking will lead to energy loss. MPPT algorithms like P&O and INC typically experience delays in adjusting the system's operating point. MPPT performance that is not adaptive to changes in irradiance will result in low tracking efficiency and power oscillations (Deo & Setianto, 2024). Therefore, sensitivity to irradiance becomes an important indicator in assessing the effectiveness of an algorithm.

In the literature study, fuzzy logic-based and neural network algorithms showed more adaptive performance to changes in irradiance. This is because the method uses a heuristic and learning approach to map input conditions to more accurate tracking responses (Imran & Rabbani, 2022). When irradiance drops drastically, this algorithm can immediately adjust the system's operating point without experiencing large oscillations. The ability to generalize patterns of change makes this algorithm superior in dynamic weather environments. However, it still requires initial training and proper parameter tuning. Its effectiveness heavily depends on the accuracy of the training data and the design of the control system.

Temperature also plays an important role in influencing the characteristics of PV systems, although its impact is not as rapid as irradiance. As the ambient temperature increases, the maximum voltage of the PV module decreases, leading to a reduction in generated power. If the MPPT algorithm doesn't account for temperature factors, the tracking point can deviate from the actual MPP. Algorithms that include temperature as an input variable, such as ANNs and some fuzzy methods, tend to be more stable in maintaining power efficiency. In extreme heat conditions, conventional algorithms often do not provide accurate responses (Aldi et al., 2022). Therefore, sensitivity to temperature becomes a distinct advantage for artificial intelligence-based algorithms.

Experimental research also shows that rapid temperature changes, for example due to heat reflection from surfaces or inadequate ventilation, can disrupt the stability of MPPT tracking. In such scenarios, the algorithm's response speed to temperature is crucial. Some optimization-based methods like PSO show quite good capability in adjusting particle positions towards a new MPP due to temperature changes (Rosales et al., 2024). However, this method requires a significant amount of iteration and processing time. If the temperature changes faster than the PSO iteration cycle, tracking can lag behind. Therefore, integrating real-time temperature sensors with responsive algorithms can improve tracking accuracy.

In the combination of irradiance and temperature changes, the performance of MPPT becomes increasingly challenging to maintain optimally. Some algorithms are only optimal in responding to one variable and fail when both variables change simultaneously. For example, P&O can work well when the temperature is constant but fails when the irradiance changes rapidly. Conversely, hybrid methods like ANN-FLC or PSO-FLC offer more consistent performance because they consider multiple variables simultaneously (Apriadi et al., 2024). The hybrid method also allows for integration into smart grid systems for real-time data-driven decision-making, making the multi-variate approach superior in the future.

From a practical implementation perspective, MPPT systems installed in locations with tropical and unstable weather, such as Indonesia, must be designed considering the high dynamics of irradiance and temperature. Literature studies show that geographical location significantly influences algorithm effectiveness. In areas with large daily irradiance variations and high daytime temperatures, machine learning-based MPPT algorithms show higher efficiency than conventional algorithms. Adjusting to local data is highly recommended in the model training process (Sawant & Khadapkar, 2022). Additionally, the design of the adaptive control system must also consider the load connected to the PV so that maximum power can be absorbed stably. The influence of local weather on algorithm design is an important aspect in the future development of MPPT systems.

Generally, sensitivity to changes in irradiance and temperature is a key parameter in evaluating MPPT algorithms under dynamic conditions. It's not enough to rely on just one type of algorithm for all conditions, as the system's response is highly dependent on the type of weather changes occurring. Therefore, future research needs to focus on algorithms that are adaptive, intelligent, and capable of predicting environmental changes. The use of real-time weather sensors integrated with the MPPT control system is also a strategic step to improve efficiency. With a more holistic and data-driven approach, PV systems can continue to generate power optimally even in the face of unpredictable weather challenges. This is important to sustainably support the transition to renewable energy.

Latest Research and Innovation Trends

In recent years, the trend in MPPT research has shown a shift from conventional algorithms to more complex and adaptive approaches. One of the key innovations is the development of hybrid algorithms, which combine two or more MPPT methods to improve efficiency and stability. Combinations such as P&O with Fuzzy Logic or INC with PSO have been tested in various studies to overcome the weaknesses of each method (Siddik, 2023). The goal is to leverage the tracking speed of conventional methods and the accuracy of intelligence-based methods. The results show a significant performance improvement, especially in dynamic weather conditions. This makes hybrid algorithms increasingly popular in the development of modern MPPT systems.

One form of hybrid MPPT that has been widely researched is the integration of Fuzzy Logic Control (FLC) with Particle Swarm Optimization (PSO). In this scheme, FLC serves as the main control, while PSO optimizes the fuzzy parameters to match the current weather conditions. The advantage of this approach is its ability to adaptively adjust parameters based on changes in irradiance and temperature. Research shows that this method can reduce oscillations and accelerate convergence towards the MPP (Inrawong et al., 2024). However, its implementation requires a more complex control system and fast data processing. Therefore, the use of hybrid MPPT requires more advanced hardware support.

As artificial intelligence technology advances, many researchers are beginning to apply Artificial Intelligence (AI) and Machine Learning (ML) in MPPT algorithms. Methods such as Artificial Neural Networks (ANN), Support Vector Machines (SVM), and Deep Learning are used to predict the MPP based on real-time environmental data. The main advantage of this approach is its ability to recognize complex patterns of irradiance and temperature changes, and to track with greater precision. AI-based algorithms also have the potential to continuously learn and improve their performance as more data becomes available. Nevertheless, the main challenge lies in the need for a large and representative training dataset (Oktaviani & Abdulloh, 2024). Additionally, the process of training and tuning the model can be time-consuming and require in-depth technical knowledge.

The integration of machine learning with MPPT has enabled the development of predictive systems, where the MPP is not only tracked reactively but also predicted based on previous data trends. For example, an ANN system can be trained to recognize specific weather patterns and prepare the PV system to adjust its operating point before changes in irradiance occur. This approach can significantly reduce power loss during transitions in weather conditions. Additionally, this predictive method is capable of increasing the system's lifespan by reducing voltage and current oscillations (Pal et al., 2024). Literature studies indicate that predictive approaches have great potential for implementation in large-scale systems such as solar farms. However, its reliance on prediction accuracy makes the quality of input data extremely important.

In addition to algorithm development, recent innovations also include real-time MPPT implementation on hardware such as microcontrollers and Digital Signal Processors (DSPs). This technology allows for maximum power point tracking to be performed directly on the PV system control unit without the need for manual intervention. By using irradiance and temperature sensors directly connected to the controller, the MPPT system can adjust its parameters every second. This is especially important in environments with rapidly changing weather conditions. The main challenge in real-time implementation is maintaining a balance between processing speed and algorithm accuracy (Zhao et al., 2024). Therefore, choosing a lightweight yet effective algorithm becomes a key factor.

Several pilot projects have successfully implemented AI-based real-time MPPT systems at industrial and residential scales. This system not only maximizes the generated power but is also capable of automatically monitoring and diagnosing solar panels and inverters. Through connection to the Internet of Things (IoT), the system can be controlled and monitored remotely, thus supporting the concept of a smart grid. This innovation opens up opportunities for integrating MPPT with cloud computing-based smart energy management (Sree & Baskar, 2024). By leveraging big data analytics, the system can adapt its tracking strategy based on short-term weather predictions and estimated energy load. This marks a new era of intelligent and highly connected MPPT.

Nevertheless, the adoption of this technology still faces obstacles in the form of implementation costs, system complexity, and the need for technical training for operators. In developing countries, limited access to advanced hardware and high-quality weather data poses a unique challenge. Therefore, research trends are also beginning to focus on developing efficient yet simple intelligent algorithms that can be widely implemented. Approaches like fuzzy logic-based adaptive P&O or lightweight ANNs are a compromise between high performance and affordability. Adapting algorithms to local conditions and the technical capabilities of end-users is an important focus in system design (Varma & Priyanka, 2022). This aims to enable the application of advanced MPPT technology in various contexts, not just in laboratories or large projects.

Overall, the trend in MPPT innovation is leading to the development of systems that are more adaptive, predictive, and integrated in real-time. The combination of hybrid algorithms, artificial intelligence, and digital technology unlocks significant potential to improve the efficiency of photovoltaic systems under dynamic weather conditions. Future research needs to emphasize collaboration between electrical engineering, informatics, and climatology disciplines to create a truly intelligent MPPT system. Additionally, field testing and experimental validation remain crucial aspects in ensuring real-world implementation feasibility. With the support of sustainable innovation, MPPT will be a key component in the transition towards reliable and efficient renewable energy. This progress is expected to accelerate the achievement of global clean energy targets.

CONCLUSION

Based on the results of the literature review, it can be concluded that no single MPPT algorithm is absolutely superior in all conditions. Conventional algorithms like P&O and INC are still relevant for simple systems with relatively stable weather due to their ease of implementation. However, in dynamic weather conditions, artificial intelligence-based algorithms such as Fuzzy Logic, Artificial Neural Network, and Particle Swarm Optimization show more efficient, responsive, and stable tracking performance. Hybrid algorithms that combine the advantages of several methods have also proven effective in improving the efficiency of PV systems. Therefore, the selection of an MPPT algorithm needs to consider the specific requirements of the system, including the operating environment, computational capacity, and application scale. A customized approach will result in optimal MPPT performance and support the sustainability of the solar energy system.

To improve the performance of the MPPT system in the future, it is recommended to further develop adaptive hybrid algorithms, particularly those capable of responding to changes in irradiance and temperature in real-time. Combining artificial intelligence with lightweight conventional methods can create efficient yet affordable solutions. Additionally, field experimental tests are needed to validate the algorithm's performance in real-world conditions, as simulations alone do not always represent the complexity of the actual environment. Future research also needs to integrate MPPT with IoT-based smart energy monitoring and management systems and weather forecasting. Multidisciplinary collaboration between engineering, data science, and renewable energy fields will accelerate innovation in the development of more reliable and efficient photovoltaic systems. Thus, MPPT technology can contribute maximally to supporting the global transition towards clean energy.

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