NIJBAS
Publications 2024

OPEN ACCESS
ONLINE ISSN: 2992-5797
PRINT ISSN: 2992-6122

NEWPORT INTERNATIONAL JOURNAL OF BIOLOGICAL AND APPLIED SCIENCES (NIJBAS)

Volume 6 Issue 2 Page 1-8, 2025

https://doi.org/10.59298/NIJBAS/2025/6.2.1800

Maximum Power Point Tracking (MPPT) Techniques for Hybrid Solar PV-Wind Turbine Energy Systems

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ABSTRACT

The integration of hybrid solar photovoltaic (PV) and wind turbine systems has garnered significant attention in addressing the global demand for sustainable and reliable energy sources. These hybrid systems offer operational advantages, especially in off-grid and remote areas where extending centralized power infrastructure is impractical. A crucial aspect of such hybrid systems is the optimization of power extraction, which is achieved through Maximum Power Point Tracking (MPPT) techniques. This paper presents a review of the key MPPT methods used in hybrid PV-wind systems, including Perturb and Observe (P&O), Incremental Conductance (INC), Fuzzy Logic Control (FLC), and Artificial Neural Networks (ANN). The paper compares their operational characteristics, highlighting their advantages, limitations, and suitability under different environmental conditions. Moreover, the paper explores two MPPT architectures for hybrid systems: independent MPPT units for each energy source and a unified MPPT controller that integrates advanced algorithms. The study aims to provide insights into the optimal selection of MPPT techniques to enhance the efficiency and reliability of hybrid renewable energy systems.

Keywords: Hybrid energy system, MPPT, solar PV, wind turbine, FLC, ANN, adaptive control

INTRODUCTION

The escalating global demand for clean and sustainable energy has spurred significant interest in the deployment of renewable energy systems, particularly in hybrid configurations [1,2,3,4]. Among the various combinations, the integration of solar photovoltaic (PV) and wind turbine systems has emerged as a promising strategy to enhance energy security and reduce dependence on fossil fuels. Hybrid solar PV–wind systems offer several operational advantages, particularly in off-grid and remote areas where extending centralized power infrastructure is economically or geographically unfeasible [5,6,7]. The complementary nature of solar and wind resources where solar irradiance is often abundant during the day and wind tends to be stronger at night or during stormy weather contributes to better load matching and improves the reliability of power supply [8,9,10]. Despite their synergistic behavior, both solar PV and wind turbine systems exhibit nonlinear voltage-current (I–V) and power-voltage (P–V) characteristics due to their dependence on rapidly fluctuating environmental variables such as irradiance, temperature, and wind speed [11,12]. As a result, the power output from these systems is inherently variable and suboptimal if not regulated in real time [13]. To address this issue, Maximum Power Point Tracking (MPPT) techniques are employed to ensure that each energy source operates at its optimal power point under varying conditions. MPPT is a critical control strategy embedded in power electronic converters to dynamically adjust the operating point of the system in response to environmental changes [14]. In solar PV systems, MPPT algorithms adjust the duty cycle of DC-DC converters to match the panel voltage to the MPP, while in wind turbines, MPPT often involves adjusting the rotor speed or load characteristics based on turbine-specific power curves [15,16]. Efficient MPPT not only maximizes energy extraction but also enhances the overall system efficiency, reduces losses, and improves the lifespan of the power electronics involved [17,18]. Over the years, a wide array of MPPT techniques has been developed and deployed. Conventional methods such as Perturb and Observe (P&O) and Incremental Conductance (INC)

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are widely used due to their simplicity and ease of implementation [19]. However, their performance often degrades under rapidly changing environmental conditions, leading to oscillations around the MPP and delayed tracking. To overcome these limitations, intelligent control methods such as Fuzzy Logic Control (FLC) and Artificial Neural Networks (ANNs) have been introduced [19,14]. These advanced techniques leverage computational intelligence to achieve faster and more accurate tracking, especially in complex and dynamic hybrid energy systems. Given the increasing adoption of hybrid renewable energy systems, the selection of an appropriate MPPT strategy becomes essential to achieving optimal performance. This research reviews the MPPT techniques applicable to hybrid solar PV-wind systems, compares their operational characteristics, and highlights their suitability under various environmental and system conditions. The aim is to provide insight into the strengths and limitations of each method and to guide future developments in MPPT control strategies for hybrid renewable energy integration.

MPPT Methods for PV-Wind Systems

MPPT algorithms are integral to the optimal operation of hybrid renewable energy systems [20, 21]. Their primary objective is to extract the maximum possible power from both PV modules and wind turbine generators under continuously varying environmental conditions. This section outlines and evaluates key MPPT techniques commonly employed in PV-wind hybrid systems, with attention to their working principles, advantages, and limitations in engineering applications [22].

Perturb and Observe (P&O) Method

The Perturb and Observe (P&O) method is one of the most widely implemented Maximum Power Point Tracking (MPPT) techniques, primarily due to its simplicity and minimal computational requirements [19]. The method operates by periodically perturbing (incrementing or decrementing) the duty cycle of a DC-DC converter and observing the corresponding change in output power. If the perturbation results in an increase in power, the algorithm continues in the same direction, whereas if the power decreases, the direction of the perturbation is reversed [23]. This straightforward approach offers several advantages, including ease of implementation with low-cost microcontrollers and minimal system modeling. However, it also has drawbacks, such as oscillations around the Maximum Power Point (MPP), which result in steady-state power loss [24]. Additionally, the method's performance is reduced under rapidly fluctuating irradiance or wind speed, leading to tracking errors that affect the system's efficiency.

Incremental Conductance (INC) Method

The Incremental Conductance (INC) method enhances the tracking accuracy of the Maximum Power Point (MPP) by comparing the incremental conductance ($\Delta I/\Delta V$) with the instantaneous conductance (I/V) [25]. At the MPP, the slope of the power-voltage (P-V) curve is zero, meaning $dP/dV = 0$, which corresponds to the relationship $\Delta I/\Delta V = -I/V$. This fundamental relationship is used to determine the direction of voltage adjustment, allowing the system to track the MPP more accurately [26]. The INC method offers several advantages, including improved tracking accuracy under rapidly changing atmospheric conditions and the ability to determine the direction toward the MPP without the oscillations commonly observed in the Perturb and Observe method. However, it also has some drawbacks, such as the need for precise voltage and current measurements, which can increase system complexity [27]. Additionally, the control logic required for the INC method is more complex compared to that of the P&O method.

Fuzzy Logic Control (FLC)

Fuzzy Logic Control (FLC) utilizes a set of linguistic rules and fuzzy inference mechanisms to adjust the operating point of a converter [28]. The inputs typically include the error, which is the difference between the current and previous power, and the change in error. These inputs are processed through fuzzy logic systems to generate outputs that determine the adjustment magnitude and direction for tracking the Maximum Power Point (MPP) [29]. FLC offers several advantages, such as its effectiveness in handling system nonlinearities and uncertainties, as well as its robust performance under noisy or imprecise input measurements. These characteristics make it highly adaptable to dynamic environments. However, the method also has some drawbacks. The design of membership functions and the fuzzy rule base requires expert knowledge, which can make the initial setup complex. Additionally, if the fuzzy system is not properly tuned or adapted to the specific system conditions, its performance may degrade, leading to suboptimal tracking efficiency.

Artificial Neural Networks (ANNs)

Artificial Neural Network (ANN)-based MPPT systems are data-driven approaches that leverage trained models to estimate the Maximum Power Point (MPP) based on real-time environmental variables such as solar irradiance, temperature, and wind speed [30]. In an ANN-based system, the inputs are processed through a multi-layered network of artificial neurons, which adjust the weights of the connections based

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on training data [29]. The network then generates optimal control signals for the converter, enabling efficient power tracking. One of the key advantages of ANN-based MPPT systems is their ability to model complex, nonlinear relationships, making them highly effective at predicting the MPP under a wide range of environmental conditions [32]. Additionally, these systems exhibit superior tracking performance, especially in scenarios involving partial shading or hybrid energy systems, where traditional methods may struggle to accurately locate the MPP. However, ANN-based systems also come with notable drawbacks. They require extensive training using large, high-quality datasets to ensure accurate and reliable performance. Furthermore, the computational resources and memory required for processing these datasets and executing the model can be significant, making ANN-based MPPT systems less suitable for low-cost embedded systems with limited processing power [32].

Hybrid MPPT Architecture

In hybrid systems, the MPPT is typically designed to optimize the energy harvest from both PV and wind energy sources. There are two main approaches to hybrid MPPT architecture [33,34]:

1. **Independent MPPT Units**: In this approach, separate MPPT algorithms are used for each energy source. For example, the P&O method may be employed for the PV system, while a Tip Speed Ratio (TSR) method could be used for the wind turbine. This allows each energy source to operate independently, ensuring maximum power extraction from both systems according to their specific characteristics [35,36].
2. **Unified MPPT Controller**: Alternatively, a unified MPPT controller can be implemented using intelligent algorithms, such as a fusion of Artificial Neural Networks (ANN) and Fuzzy Logic Controllers (FLC). This approach combines the strengths of both ANN's ability to model complex nonlinear relationships and FLC's capacity to handle system uncertainties, providing a more integrated and robust solution for tracking the maximum power point across both energy sources simultaneously [37,38].

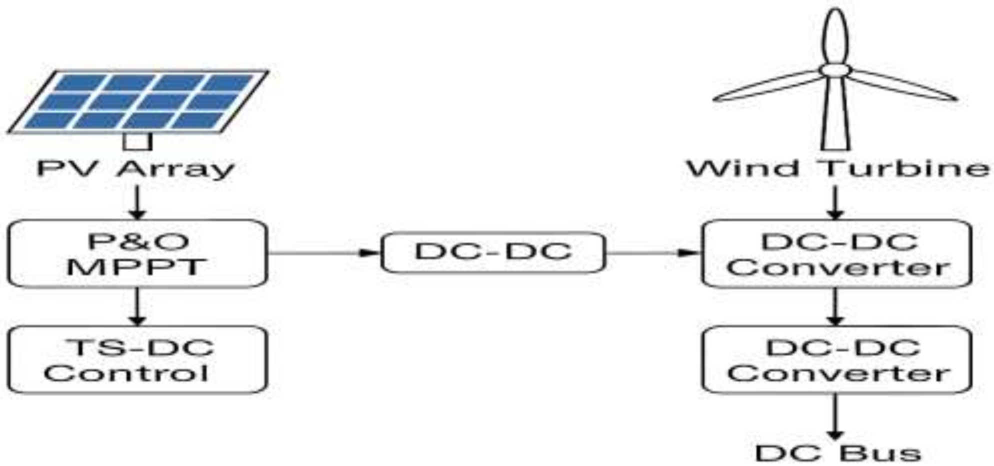

Figure 1: Block diagram of a hybrid PV-wind MPPT system architecture with separate controllers

This hybrid MPPT architecture, as illustrated in Figure 1, facilitates the optimal management of multiple renewable energy sources [39,40]. It ensures that each system operates at its maximum efficiency, adapting to the fluctuating environmental conditions. By dynamically adjusting the power output of each source, this architecture enhances the overall performance and reliability of the hybrid system, making it well-suited for environments with variable solar and wind conditions.

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Table 1: Comparative Analysis of the MPPT Units

Aspect	Independent MPPT Units	Unified MPPT Controller
Control Approach	Separate MPPT for each source (PV, Wind)	Single controller for both PV and Wind, using intelligent algorithms (ANN + FLC)
Algorithm	P&O for PV, TSR for Wind	Fusion of ANN and FLC
Complexity	Lower complexity, easier to implement	Higher complexity requires advanced algorithms
Energy Optimization	Independent optimization per source	Optimizes the combined energy output from both sources
Cost	Typically lower due to simpler control systems	Higher due to the need for computational power and advanced controllers
Efficiency	May not fully account for system interactions	Potentially higher, as it adapts to both sources' conditions simultaneously
Adaptability	Limited to individual source conditions	Highly adaptive, can adjust to both PV and wind conditions
Implementation Difficulty	Easier to implement	More challenging due to the integration of algorithms

Table 1 illustrates that the choice between Independent MPPT Units and a Unified MPPT Controller hinges on the specific design requirements and constraints of the system. If the priorities are simplicity and cost-effectiveness, the independent MPPT approach may be more suitable. However, for a more integrated solution that offers potentially higher efficiency, especially in systems exposed to varying environmental conditions, the unified MPPT controller becomes the preferred option [41,42,43]. Utilizing intelligent algorithms such as Artificial Neural Networks (ANN) and Fuzzy Logic Controllers (FLC), the unified approach provides a more robust and adaptive method for maximizing power extraction, ensuring optimal performance under diverse and dynamic conditions.

Comparative Summary

Table 2: Performance Comparison of MPPT Techniques for Hybrid Power Systems

Technique	Tracking Speed	Tracking Accuracy	Algorithmic Complexity	Suitability for Hybrid Systems
P&O	Medium	Low to Medium	Low	Suitable for systems with moderate performance requirements.
INC	High	High	Medium	Well-suited for systems with a need for higher efficiency and faster tracking.
FLC	High	High	High	Ideal for complex hybrid systems, offering improved performance in dynamic conditions.
ANN	Very High	Very High	Very High	Optimal for hybrid systems with abundant training data, delivering superior performance under varying conditions.

The refinements made to the comparison in Table 2 focus on improving clarity and precision in describing the various aspects of MPPT techniques. First, the term Tracking Speed was clarified to avoid any confusion, ensuring it aligns with the standard terminology used in MPPT systems [44,45]. Similarly, "Tracking Accuracy" was specified to more precisely reflect the quality of maximum power point tracking, providing a clearer understanding of each technique's performance [46,47]. The term "Algorithmic Complexity" was refined to explicitly address the computational demands associated with each technique, offering a more accurate representation of their respective resource requirements [48,49]. Finally, the Suitability for Hybrid Systems category was expanded to provide more detailed descriptions of how each technique meets the specific needs of hybrid systems, offering a better understanding of the contexts in which each method excels [50,51]. These adjustments enhance the table's scientific rigor by ensuring precision in terminology and improving the overall explanation of each technique's characteristics and suitability.

CONCLUSION

Hybrid solar PV-wind systems present a promising solution for addressing energy security and sustainability, particularly in off-grid and remote regions. The integration of effective MPPT techniques is vital to maximize the efficiency of these systems by ensuring optimal power extraction from both solar and wind energy sources. Among the various MPPT methods, P&O and INC offer simplicity and moderate

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PRINT ISSN: 2992-6122

performance, while FLC and ANN provide superior tracking accuracy and adaptability, especially in dynamic environments. The choice of MPPT strategy depends on the specific system requirements, such as complexity, cost, and energy optimization goals. Furthermore, the adoption of a unified MPPT controller combining intelligent algorithms like ANN and FLC offers a robust and highly adaptable solution for hybrid systems, ensuring optimal energy management across both solar and wind sources. Future developments in MPPT algorithms should focus on enhancing the adaptability and efficiency of hybrid renewable energy systems, with an emphasis on real-time optimization to mitigate environmental fluctuations.

Conflict of Interest

The author declares no conflict of interest regarding this publication.

Acknowledgments

The author expresses gratitude to Kampala International University for academic support and resources provided during the preparation of this communication.

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ONLINE ISSN: 2992-5797
PRINT ISSN: 2992-6122

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CITE AS: Kiiza Ritah and Ssebagala Mirabel (2025). Maximum Power Point Tracking (MPPT) Techniques for Hybrid Solar PV-Wind Turbine Energy Systems. NEWPORT INTERNATIONAL JOURNAL OF BIOLOGICAL AND APPLIED SCIENCES, 6(2):1-8.
https://doi.org/10.59298/NIJBAS/2025/6.2.1800

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