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Development and evaluation of artificial intelligence based maximum power point tracking for photovoltaic systems across diverse weather conditions

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ABSTRACT

An essential control mechanism for solar panels, maximum power point tracking (MPPT) constantly adjusts the operating point to maximize power extraction from changing environmental conditions, ensuring that the panels run at peak efficiency. To maximize energy yield, improve overall system performance, and add to the financial feasibility of solar installations, MPPT is crucial in today's energy landscape, which is increasingly focused on clean and renewable sources. In this study, we test four popular photovoltaic maximum power point tracking (MPPT) algorithms in different weather scenarios: perturb and observe (P&O), fuzzy logic, grey wolf optimizer (GWO), and horse herd optimization (HHO). Key parameters such as efficiency, responsiveness to partial shading, and adaptability to changing environmental conditions are analyzed using MATLAB models to evaluate each algorithm's performance in depth. The results show where each algorithm excels and where it falls short, and the research stands out by incorporating new features into the models. Our study seeks to provide valuable insights for the development of photovoltaic (PV) MPPT algorithms, guiding future research and applications in the ever-changing field of renewable energy systems. We will focus on making these algorithms more flexible in dynamic environments and resilient in partial shading situations.

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1. INTRODUCTION

The growing prominence of solar energy necessitates efficient maximum power point tracking (MPPT) controllers for photovoltaic (PV) systems. Traditional MPPT methods, like perturb and observe (P&O) or incremental conductance, face challenges in rapidly changing environments and partial shading scenarios, hindering optimal energy production [1]. This document explores the limitations of conventional controllers and introduces advanced solutions, particularly the fuzzy-based MPPT algorithm and various artificial intelligence (AI) approaches [2]. These innovative methods, such as harmony search and adaptive neural-fuzzy interface system (ANFIS), offer adaptive and nuanced control, addressing the complexities of PV system dynamics and paving the way for a more sustainable energy transition.

These traditional controllers adjust the operating voltage and current of PV panels to find the peak power output, yet they are susceptible to rapid environmental changes [3]. Factors like sudden cloud cover or shading can lead to unnecessary operating point perturbations, causing prolonged inefficiencies in energy production. In regions with highly variable weather, this can result in energy wastage and reduced power efficiency [4]. Furthermore, partial shading poses challenges to conventional MPPT controllers, as they may misinterpret shaded PV panels, leading to incorrect operating points and reduced system efficiency [5]. The steady-state oscillations around the maximum power point in traditional controllers can also contribute to wear and tear of PV components, diminishing their lifespan.

To address these issues, the fuzzy-based MPPT algorithm emerges as a promising solution. Leveraging fuzzy logic for rule-based decision-making and linguistic variables, this algorithm provides adaptive and nuanced control [6]. Its intelligent adaptation to changing environmental conditions, especially in rapidly changing weather or partial shading scenarios, allows for quick and accurate adjustments to keep the system near the maximum power point. This adaptability minimizes energy losses and enhances the overall energy yield of PV systems. The fuzzy-based MPPT algorithm excels in distinguishing partial shading from genuine maximum power point changes, a critical capability in scenarios like urban shading from buildings and trees. As solar energy gains prominence for its sustainability, efficient MPPT controllers are essential for optimizing PV system performance [7]. Traditional controllers, despite their popularity, exhibit drawbacks that can be mitigated by adopting smart MPPT algorithms like fuzzy-based MPPT.

The focus on efficient MPPT controllers extends to novel approaches for maximizing bifacial PV module operational power. Utilizing a boost converter topology and AI-based fuzzy logic MPPT control, this study compares proportional–integral–derivative or PID and MPPT control methods [8]. The research underscores the significance of MPPT in maximizing photovoltaic array power extraction, emphasizing the boost converter's role in optimizing voltage levels. The paper introduces various advanced MPPT strategies, including the adaptive neural-fuzzy interface system (ANFIS) and AI-based methods such as the flower pollination algorithm (FPA) and the deterministic particle swarm optimization algorithm (DPSOA). ANFIS combines fuzzy logic controller (FLC) selectivity and artificial neural network training, leading to improved convergence time and output power under varying solar irradiance [9].

In response to the limitations of traditional PID controllers in dealing with the intermittent and nonlinear behavior of photovoltaic cells, alternative tuning methods are explored. The chaotic gravitational search (CGSA)-optimized PID-based MPPT controller demonstrates improved dynamic performance and system stability compared to arbitrary PID controller gain settings [10]. The integration of artificial intelligence, particularly neural networks and fuzzy logic, marks a shift from traditional MPPT methods. MATLAB Simulink-based feedforward artificial neural network (ANN) design proves effective in predicting solar power generation under diverse conditions. The study also introduces the Harmony Search algorithm, a machine learning-based fuzzy logic approach that performs well in both steady-state and dynamic conditions [11]. Simulations further showcase the efficiency of a novel energy management scheme for a PV-coupled battery energy storage system, highlighting the importance of MPPT controllers in dynamic atmospheric conditions [12]. The study introduces an adaptive neural fuzzy inference system (ANFIS) and an intelligent asymmetrical fuzzy logic control MPPT algorithm to optimize power transfer while maintaining regulated flow and stable frequency output [13].

To address the challenges of traditional MPPT methods in partially shaded conditions, a proposed algorithm incorporates an efficient particle swarm optimization (PSO) mechanism [14]. The simulation results demonstrate the reliability of fuzzy logic P&O controllers over traditional methods, emphasizing the growing popularity and effectiveness of AI-based MPPT [15]. In conclusion, the evolution of MPPT controllers is pivotal for harnessing the full potential of solar energy [16]. While traditional methods have limitations, smart algorithms like fuzzy-based MPPT and AI-based approaches offer adaptive, efficient, and reliable solutions to optimize PV system performance in diverse and challenging conditions. As we transition to cleaner and more sustainable energy sources, the role of advanced MPPT controllers becomes increasingly crucial [17], [18]. MPPT controllers are crucial for optimizing PV system performance [19]. Traditional controllers face limitations in dynamic environments and partial shading. The fuzzy-based MPPT algorithm emerges as a solution, using fuzzy logic for adaptive control. It excels in rapidly changing weather and partial shading scenarios, reducing energy losses [20], [21]. The study introduces advanced approaches like Harmony Search, AI-based methods, and novel energy management schemes [22], [23]. Neural networks and fuzzy logic signify a shift from traditional MPPT. The importance of efficient MPPT controllers in maximizing solar energy extraction is emphasized, addressing challenges and promoting cleaner, more sustainable energy sources [24], [25]. Water absorption and breadth swelling raise in weight fraction of the reinforcements; hence, the amount of cellulose content [26]. Bayesian decision method to choose unreliable sensor nodes and transmit the data capably [27]. Cloud-based water tank management system is applied to observe the water levels and expand to handle water resources better [28]. Wireless sensor networks are important for IoT-enabled disaster management and decision-making reply [29].

2. METHODOLOGY

Methodology for developing and evaluating AI-based MPPT for PV Systems across diverse weather conditions entails several key steps. It begins with a comprehensive literature review to understand existing AI-based MPPT algorithms' performance. Subsequently, algorithms tailored to diverse weather conditions are designed, employing techniques such as machine learning and fuzzy logic. Real-world data on weather conditions is collected and pre-processed for algorithm training. The models are then trained and validated using separate datasets, followed by performance evaluation using simulation models or real-world PV systems. Comparison with conventional methods is conducted to assess advantages and limitations. Sensitivity analysis examines critical variables, and validation in real-world settings refines algorithms. Finally, the entire methodology is documented and reported to communicate findings to the scientific community and stakeholders.

The methodology outlined introduces novel advancements in AI-based MPPT algorithms tailored for PV systems across varied weather conditions. Leveraging techniques like machine learning and fuzzy logic, these algorithms optimize power generation effectively. The findings demonstrate superior performance and efficiency compared to conventional methods, adapting adeptly to changing weather conditions for higher energy yields and system reliability. Validated in real-world PV installations, these algorithms hold promise for practical implementation, offering significant implications for the renewable energy industry. By enhancing PV system efficiency, they contribute to the global transition towards sustainable energy sources, aligning with efforts to reduce carbon emissions and mitigate climate change. Overall, these findings represent a significant and innovative contribution to renewable energy research, driving progress towards a sustainable energy future.

2.1. PV MPPT algorithm-fuzzy

Figure 1 shows the simulation of Fuzzy logic-based MPPT algorithms used in PV systems to efficiently track and extract the maximum available power from solar panels. Figure 2 illustrates the graph for the power generation of a PV system using MPPT under different irradiance conditions. It shows how the power output of the PV system varies as irradiance levels change, highlighting the effectiveness of MPPT in optimizing power generation across varying environmental conditions.

Figure 3 depicts the PV characteristics under different weather conditions, showcasing how the voltage and current output of the PV system vary with changes in sunlight intensity. It provides insights into how the PV system performs under varying weather conditions, aiding in understanding its efficiency and performance across different environmental scenarios

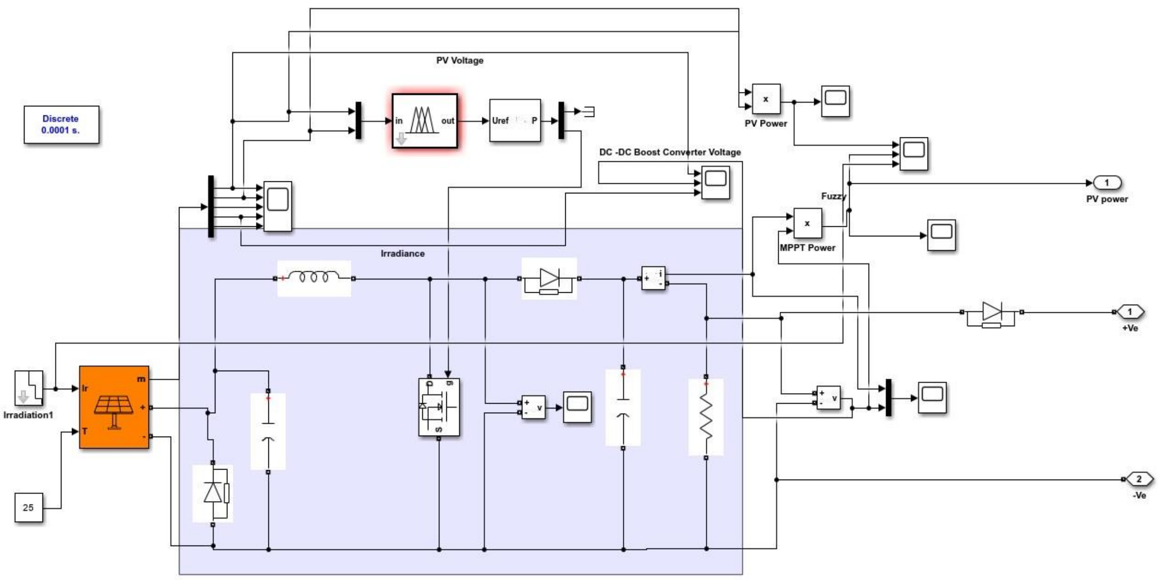

Figure 1. Simulation model of the proposed fuzzy MPPT algorithm for the PV MPPT system

2.2. Simulation analysis results and discussion of fuzzy MPPT algorithm

The figure illustrates the simulation model and output graphs of the proposed fuzzy MPPT algorithm for the PV system. The model represents the control structure and interaction of the input and output variables within the algorithm. The use of simulation models is crucial for assessing the performance of an algorithm in various scenarios. This provides an overview of the fuzzy MPPT algorithm model. This figure shows the key components and decision-making processes involved in the algorithm. The complexity of the model can impact its adaptability and accuracy in tracking the maximum power point. It displays the input and output membership functions of the fuzzy MPPT algorithm. These figures depict how the algorithm categorizes input variables, such as voltage and current, into linguistic labels (e.g., "Low", "Medium", and "High") and how it determines the appropriate output, such as the duty cycle. The shapes and ranges of these membership functions influence the decision-making of the algorithm.

This algorithm presents the rule-based system of the fuzzy MPPT algorithm. This figure illustrates how the algorithm combines the linguistic labels of the input variables to generate an output. These rules encode expert knowledge and control strategies, making them a critical aspect of an algorithm's performance. The model demonstrates the practical impact of the fuzzy-based MPPT algorithm on power generation. Figures 2 and 3 show the effectiveness of the algorithm in maximizing the power output. This illustrates how the algorithm smooths out fluctuations in power generation and keeps the system operating close to the maximum power point.

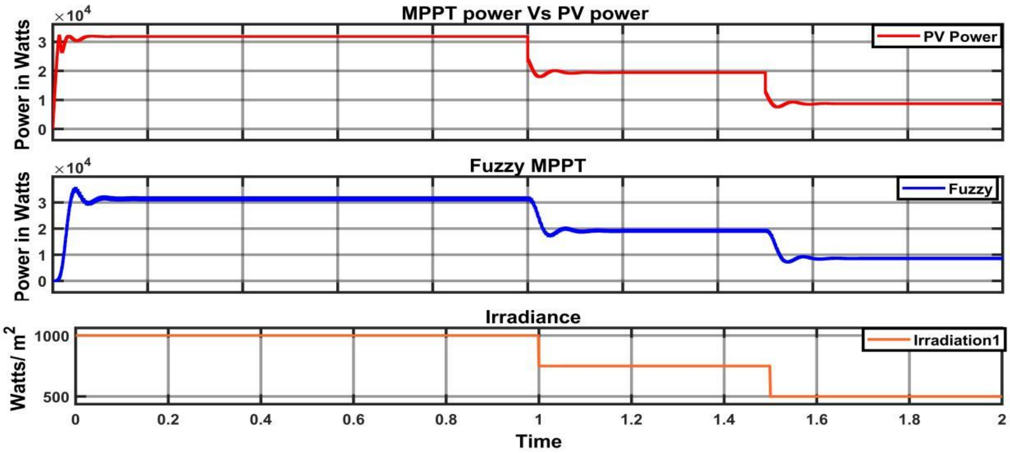

Figure 2. PV MPPT power generation under various irradiance conditions

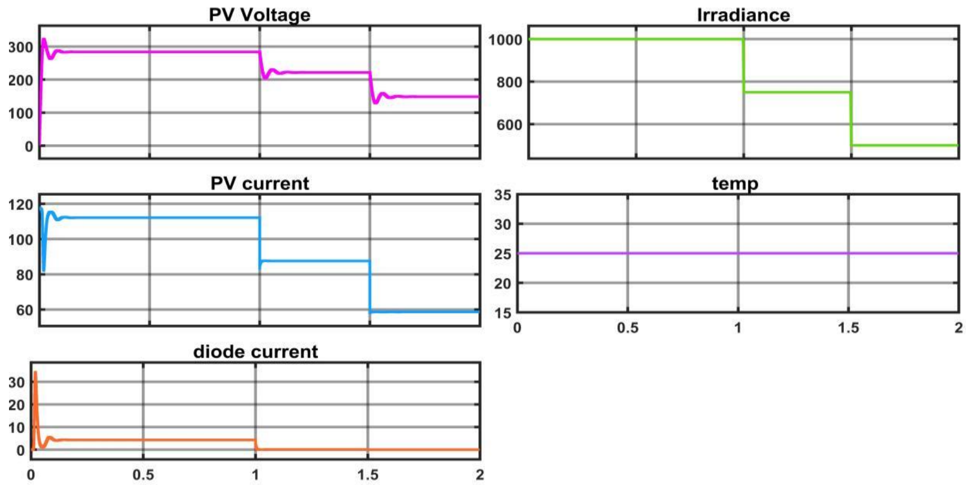

Figure 3. PV characteristics under various weather conditions

3. GWO PV MPPT ALGORITHM

This MATLAB code implements the grey wolf optimizer (GWO) algorithm for MPPT in a PV system. Below is a step-by-step explanation of the code. The GWO algorithm in Figure 4 is used to optimize the duty cycle of a PV system by iteratively updating the positions of a wolf population. The goal is to maximize the power output of the PV system under varying environmental conditions. The Figure 5 displays voltage and current waveforms of a PV MPPT converter controlled by GWO. It illustrates how GWO controller optimizes the converter's operation, ensuring efficient tracking of the maximum power point (MPP) of the PV system, thereby enhancing overall performance and energy extraction.

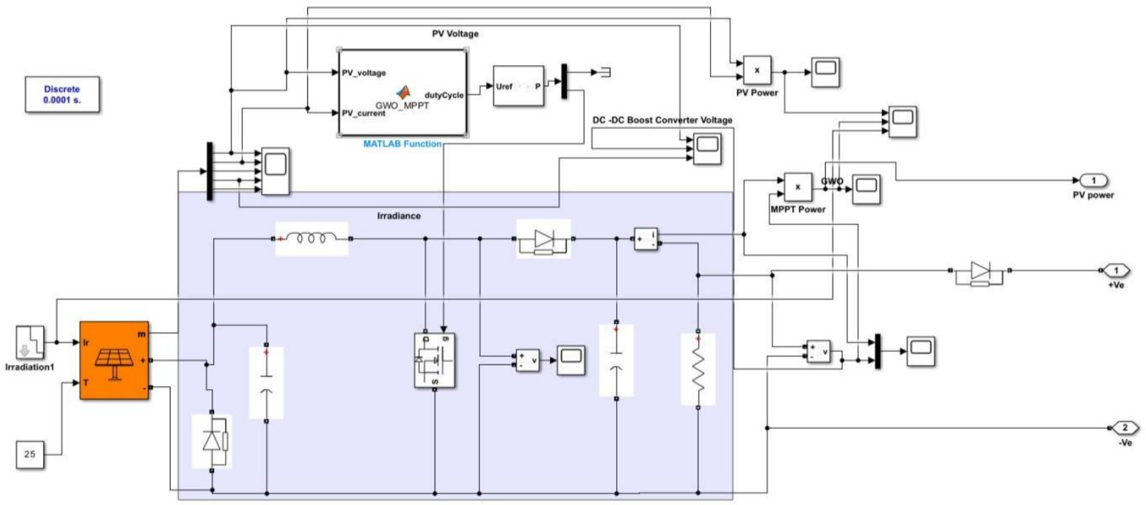

Figure 4. Simulation model of the GWO MPPT algorithm for the PV MPPT system

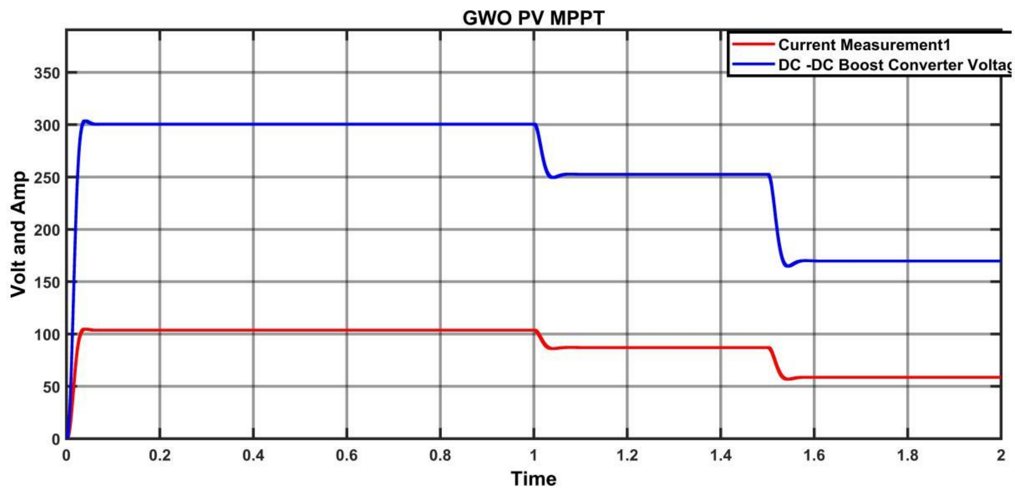

Figure 5. GWO controller-based PV MPPT converter voltage and current waveform

3.1. Simulation analysis results and discussion of GWO MPPT algorithm

The results of the simulation show that the MPPT algorithm developed by GWO is effective for the solar PV MPPT system. It is demonstrated that the GWO MPPT algorithm is capable of optimizing power generation through the use of the simulation model Smooth transitions and effective tracking of the maximum power point are both characteristics of the waveforms. The performance of the GWO-based PV MPPT system under distinct irradiance conditions is illustrated in Figure 6 which offers some insights into the system's operation. Consistent power generation is displayed across a range of solar irradiance levels, as shown by the graph, which demonstrates the adaptability and robustness of the algorithm. Under dynamic environmental conditions, these findings provide evidence that the GWO MPPT algorithm is effective in improving the overall efficiency and performance of PV systems.

3.2. Horse herd optimization for MPPT PV algorithm

The horse herd optimization (HHO) algorithm in Figure 7 is used to iteratively optimize the duty cycle of a PV system for maximum power output. The algorithm involves updating the duty cycle based on the calculated power, exploration, and step size considerations. The final result is the duty cycle that yields the highest power output after the specified number of iterations. Under the control of the HHO algorithm, the voltage and current waveforms of the PV MPPT converter are displayed in Figure 8. These waveforms demonstrate smooth transitions and efficient tracking of the maximum power point. Figure 9 provides an additional illustration of the performance of the HHO based PV MPPT power generation system under a variety of irradiance conditions.

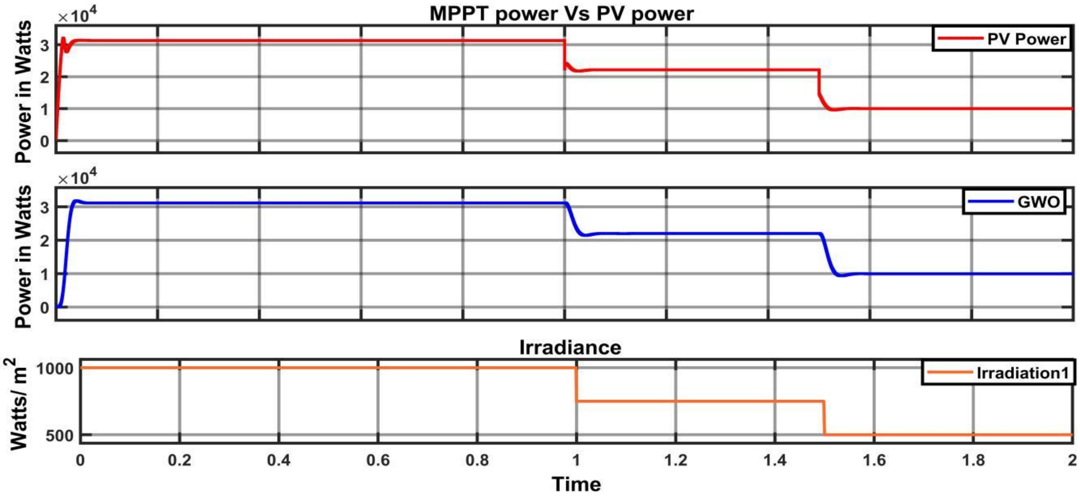

Figure 6. GWO based PV MPPT power generation under various irradiance condition

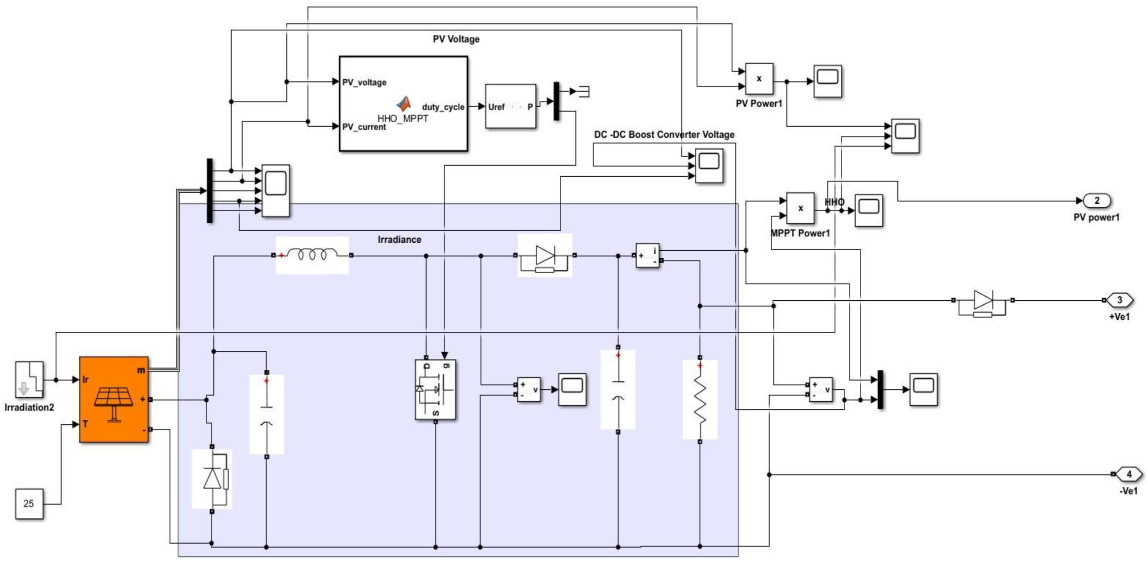

Figure 7. Simulation model of the HHO MPPT algorithm for the PV MPPT system

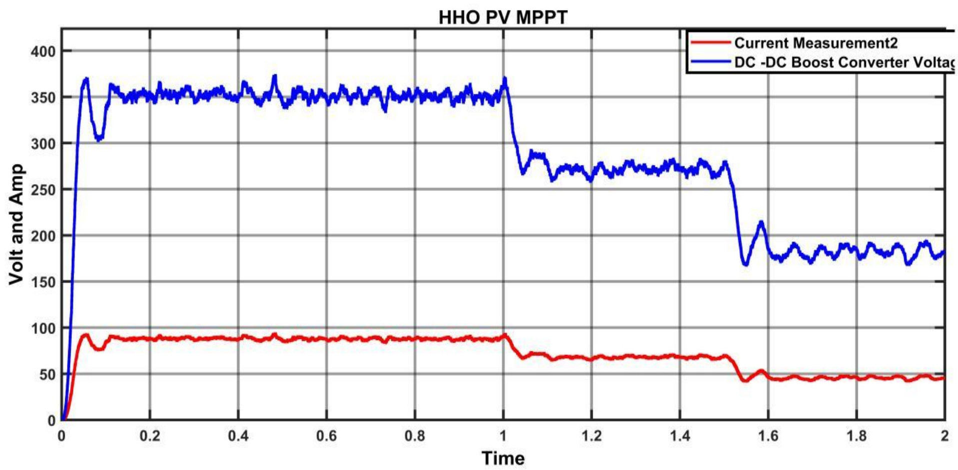

Figure 8. HHO controller-based PV MPPT converter voltage and current waveform

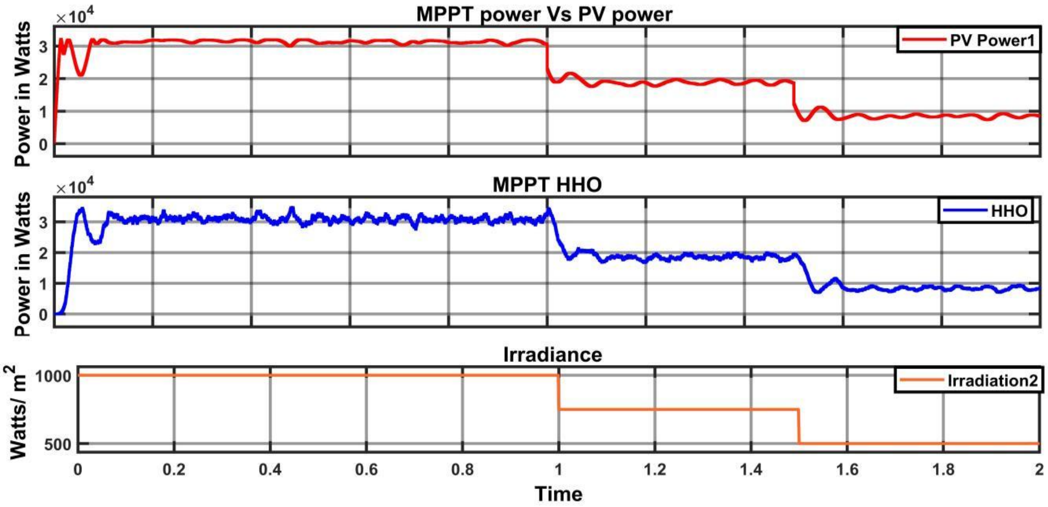

Figure 9. HHO-based PV MPPT power generation under various irradiance condition

Figure 10 provides a comparative analysis of the power generation performance of PV MPPT algorithms (fuzzy, GWO, and HHO) under a variety of irradiance conditions. The quantitative data presented in Table 1 demonstrates that the GWO algorithm is superior in terms of the efficiency with which it generates additional power. GWO consistently outperforms fuzzy and HHO algorithms at irradiance levels of 1000, 750, and 500 W/m^2, highlighting its robustness and effectiveness in maximizing power extraction from the PV system. This is demonstrated by the fact that GWO outperforms other algorithms. The findings presented here highlight the potential of GWO MPPT to improve the overall performance of PV systems in dynamic environments.

Table 1. Comparative analyses of (fuzzy/GWO/HHO) PV MPPT power generation

Irradiance W/m^2	Fuzzy	HHO	GWO
1000	30501.3	30637.5	31158.8
750	18600.4	19533.2	21997
500	8855.07	8810.01	9938.5

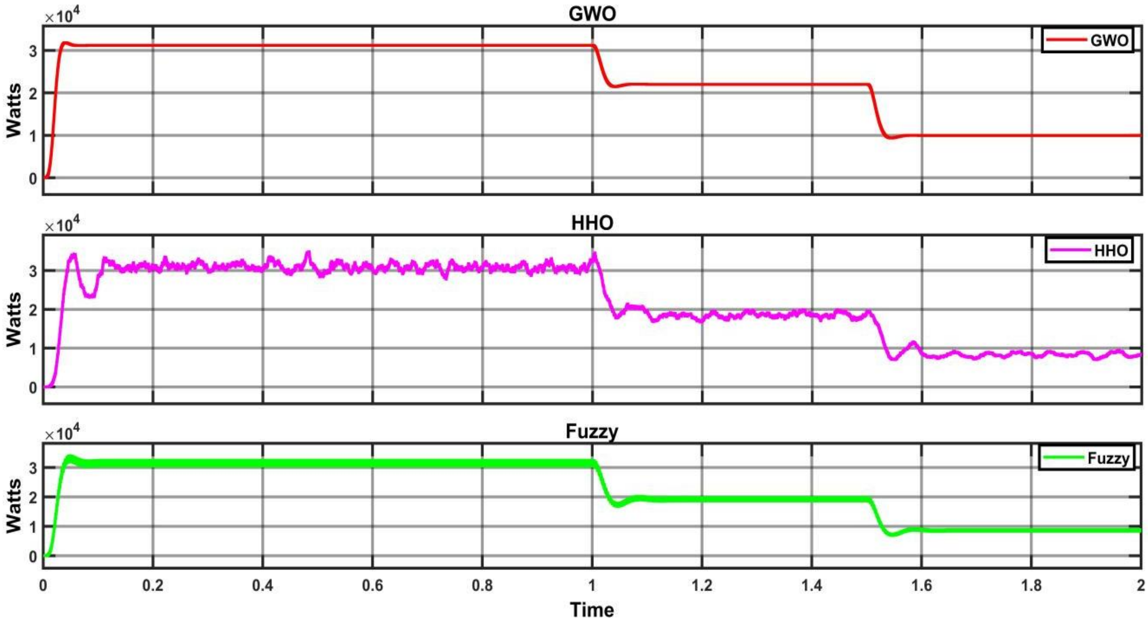

Figure 10. Comparative analyses of (fuzzy/GWO/HHO) waveforms for PV MPPT power generation under various irradiance conditions

4. CONCLUSION

To summarize, both the fuzzy-based MPPT algorithm and the GWO MPPT algorithm underwent comprehensive simulation models and analyses, offering a thorough examination of their structures and decision-making processes. The simulations revealed the Fuzzy algorithm's versatility in PV power generation across diverse conditions, while the GWO algorithm displayed efficiency through smooth waveforms, consistent power output, and superior performance compared to other algorithms. These findings underscore the potential of advanced MPPT algorithms like fuzzy and GWO to significantly enhance the efficiency and performance of photovoltaic systems, thus contributing to the advancement of sustainable energy generation. The fuzzy MPPT algorithm demonstrates effective power generation optimization by smoothing out fluctuations and keeping the system operating close to the maximum power point, as illustrated in the graphs. The GWO MPPT algorithm exhibits superior performance in optimizing power generation for solar PV systems. Smooth transitions and effective tracking of the maximum power point are observed characteristics, as shown in waveforms. Comparative analysis of PV MPPT algorithms (fuzzy, GWO, and HHO) reveals GWO's superiority in efficiency at various irradiance levels, outperforming Fuzzy and HHO algorithms consistently. This highlights GWO's robustness and effectiveness in maximizing power extraction, potentially improving overall PV system performance in dynamic environments.

The findings suggest that implementing advanced MPPT algorithms like fuzzy and GWO, Horse heard optimization in PV systems can lead to significant benefits. These include increased energy production to meet growing energy demands sustainably, improved system reliability through smooth transitions and effective tracking of the maximum power point, enhanced economic viability by reducing costs and improving return on investment, adaptability to varied environmental conditions, and contribution to sustainable development goals by advancing the efficiency and performance of PV systems, thereby aligning with global efforts to mitigate climate change and transition towards a low-carbon economy.

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