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# Hybrid Adaptive Fuzzy–Grey Wolf Optimizer MPPT for PV Systems under Dynamic Irradiance Conditions

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**Abstract**

*The increasing global demand for electrical energy and the environmental impact caused by fossil fuel consumption have accelerated the development of renewable energy technologies, particularly photovoltaic (PV) systems. However, the efficiency of PV systems is highly affected by environmental conditions such as irradiance and temperature variations. Under dynamic irradiance conditions, the output characteristics of photovoltaic systems become nonlinear, causing continuous shifts in the Maximum Power Point (MPP). Conventional Maximum Power Point Tracking (MPPT) methods, such as Perturb and Observe (P&O) and Incremental Conductance (INC), often experience limitations including oscillation, slow convergence speed, and reduced tracking accuracy during rapid irradiance changes. Therefore, an intelligent and adaptive MPPT method is required to improve the performance and stability of PV systems under dynamic operating conditions. This research proposes a Hybrid Adaptive Fuzzy–Grey Wolf Optimizer (AF-GWO) MPPT method for photovoltaic systems operating under dynamic irradiance conditions. The proposed method combines the adaptive decision-making capability of the Fuzzy Logic Controller (FLC) with the optimization performance of the Grey Wolf Optimizer (GWO) algorithm. The Adaptive Fuzzy Logic Controller is utilized to manage the nonlinear characteristics of the PV system, while the GWO algorithm is employed to optimize the membership functions and controller parameters for improved tracking performance. The entire system is modeled and simulated using*



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*MATLAB/Simulink. Several simulation scenarios were conducted under constant and rapidly changing irradiance conditions to evaluate the effectiveness of the proposed method. The performance of the Hybrid AF-GWO MPPT was compared with conventional MPPT techniques based on parameters including tracking efficiency, rise time, settling time, tracking error, and power oscillation. The simulation results demonstrated that the proposed Hybrid AF-GWO MPPT method achieved superior performance compared to conventional approaches. The proposed controller provided faster convergence toward the Maximum Power Point, reduced steady-state oscillations, improved tracking stability, and achieved tracking efficiency above 98% under dynamic irradiance conditions. The findings of this study indicate that the Hybrid Adaptive Fuzzy–Grey Wolf Optimizer MPPT method is highly effective for enhancing photovoltaic system performance under real environmental conditions. This research contributes academically to the development of intelligent hybrid MPPT techniques based on artificial intelligence and metaheuristic optimization. Practically, the proposed method has strong potential for implementation in advanced renewable energy systems to improve the efficiency, stability, and reliability of photovoltaic power generation.*

**Keywords: Photovoltaic System, Maximum Power Point Tracking, Adaptive Fuzzy Logic Controller, Grey Wolf Optimizer, Dynamic Irradiance, Renewable Energy.**

## INTRODUCTION

Electrical energy has become a primary necessity in various sectors of modern life, including industry, transportation, information technology, and households. Population growth, urbanization, digitalization, and the development of artificial intelligence-based technologies have significantly increased global electricity consumption each year. The International Energy Agency (IEA) reported that global electricity demand increased by 4.3% in 2024, higher than the 2.5% increase recorded in the previous year (IEA, 2025). This condition indicates that the world is entering an era of massive electrification that requires sustainable energy availability. (IEA, 2025).

The increasing energy demand is still predominantly supplied by fossil fuels such as coal, petroleum, and natural gas. Dependence on fossil energy creates several serious issues, including limited energy reserves, global energy price instability, and rising greenhouse gas emissions that contribute to climate change. The IEA stated that global carbon emissions remain at a high level due to the dominance of fossil fuel-based power generation in the world's electricity systems (IEA, 2024). Furthermore, the energy sector is one of the largest contributors to global $CO_2$ emissions,



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making the transition toward clean and sustainable energy systems increasingly necessary (IEA, 2024).

In response to these issues, many countries have accelerated the development of renewable energy as a sustainable and environmentally friendly energy solution. During the COP28 conference, countries worldwide agreed to triple global renewable energy capacity by 2030 in order to reduce dependence on fossil fuels (IEA, 2024). Renewable energy development is considered a strategic step to support energy security while simultaneously reducing environmental impacts caused by excessive fossil fuel consumption.

One of the renewable energy sources experiencing the fastest growth is photovoltaic (PV) solar energy. PV technology is capable of directly converting solar energy into electrical energy through the photovoltaic effect, making it environmentally friendly, flexible, and easy to implement. The IEA-PVPS reported that global PV capacity exceeded 1.6 TW in early 2024, with electricity production reaching 2,136 TWh or approximately 8.3% of global electricity demand (IEA-PVPS, 2024). This growth demonstrates that PV technology has become one of the main pillars of the global energy transition.

The development of PV technology has also been driven by decreasing solar module prices and increasing governmental policy support in many countries. The IEA noted that the decline in PV module prices in 2024 became a major factor accelerating global solar energy installations (IEA, 2024). Moreover, PV systems are predicted to contribute approximately 80% of the increase in global renewable energy capacity over the coming years due to their increasingly competitive installation costs compared to conventional power plants.

As a tropical country, Indonesia has enormous solar energy potential because it receives relatively high solar irradiance throughout the year. Indonesia's geographical conditions enable optimal utilization of solar energy to support national electricity demand, especially in remote areas with limited access to conventional power grids. Therefore, the development of PV systems has become an important strategy to support national energy mix targets and the transition toward clean energy.

Despite its enormous potential, photovoltaic systems still face several implementation challenges, particularly regarding power conversion efficiency. The output power of solar panels is highly influenced by environmental conditions such as irradiance and temperature. Variations in environmental conditions cause dynamic changes in the current-voltage characteristics of PV systems, leading to unstable system performance. This issue has become one of the primary factors limiting PV system efficiency under real operating conditions.


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The output characteristics of PV systems are nonlinear, causing the Maximum Power Point (MPP) to continuously shift according to irradiance and temperature variations. When irradiance increases or decreases, the position of the maximum power point also changes. Consequently, the system must rapidly and accurately adjust its operating conditions to maintain optimal power output. This nonlinear behavior requires a specialized control method capable of continuously tracking the maximum power point.

Under dynamic irradiance conditions such as cloudy weather, rapid cloud movement, or sudden changes in sunlight intensity, PV output power fluctuates significantly. These conditions commonly occur in real-world PV applications and make maximum power point tracking more challenging. Failure to quickly adapt to irradiance variations may lead to considerable reductions in energy conversion efficiency.

Power instability caused by irradiance fluctuations can result in power losses, reduced power quality, and decreased overall PV system performance. Therefore, an effective control method is required to maintain PV operation at the maximum power point rapidly, accurately, and stably despite dynamic environmental changes.

To address these challenges, photovoltaic systems are generally equipped with Maximum Power Point Tracking (MPPT) techniques. MPPT aims to optimize the output power of solar panels by ensuring that the system continuously operates at the maximum power point. MPPT techniques have become essential components in modern PV systems because they directly affect overall efficiency and output power quality.

Conventional MPPT methods such as Perturb and Observe (P&O) and Incremental Conductance (INC) are widely used because of their simple structure and ease of implementation. These methods can track the maximum power point with relatively low computational complexity, making them suitable for various PV applications.

However, conventional MPPT methods still suffer from several limitations, especially under rapidly changing irradiance conditions. The P&O method often experiences oscillations around the maximum power point, resulting in power losses, while the INC method tends to exhibit slower tracking responses during transient conditions. These weaknesses reduce the effectiveness of conventional methods in dynamic environmental conditions.

The advancement of artificial intelligence and optimization algorithms has encouraged the development of intelligent MPPT methods to improve maximum power point tracking performance. Artificial intelligence-based methods are considered more adaptive to nonlinear systems and capable of providing faster responses compared to conventional methods.


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Consequently, research on intelligent MPPT techniques has rapidly increased in recent years.

One of the intelligent methods commonly applied in MPPT systems is the Fuzzy Logic Controller (FLC). FLC can effectively handle nonlinear systems without requiring complex mathematical models, making it suitable for photovoltaic systems with varying characteristics. In addition, FLC provides decision-making capabilities based on linguistic rules, making it more flexible under different operating conditions.

Although FLC demonstrates relatively good performance, it still has limitations related to the design of membership functions and rule bases. In most cases, fuzzy parameters are manually designed based on expert knowledge and experience, causing system performance to depend heavily on subjective design considerations. As a result, conventional FLC methods may become less adaptive under highly dynamic irradiance conditions.

In addition to fuzzy-based approaches, metaheuristic algorithms have increasingly been utilized to improve MPPT performance in PV systems. One promising optimization algorithm is the Grey Wolf Optimizer (GWO), which is inspired by the hunting behavior and leadership hierarchy of grey wolves. GWO offers advantages such as global optimization capability, simple algorithmic structure, and fast convergence speed, making it suitable for nonlinear optimization problems.

In MPPT applications, the GWO algorithm can be utilized to optimize controller parameters so that the tracking process becomes faster and more stable. Its exploration and exploitation mechanisms enable the system to identify optimal operating points with higher accuracy compared to conventional approaches.

Several previous studies have demonstrated that hybrid methods combining fuzzy logic and metaheuristic algorithms can improve MPPT tracking efficiency compared to traditional techniques. However, most previous studies mainly focused on static irradiance or slowly varying environmental conditions, making them less effective in handling real-time dynamic irradiance changes. Moreover, some studies still exhibit limitations regarding fuzzy parameter adaptiveness and tracking stability during extreme irradiance variations.

Based on these challenges, this study proposes a Hybrid Adaptive Fuzzy–Grey Wolf Optimizer MPPT method for photovoltaic systems operating under dynamic irradiance conditions. The proposed method aims to improve tracking speed, reduce power oscillations, and enhance PV system efficiency by combining the adaptive capability of fuzzy logic with the global optimization performance of the Grey Wolf Optimizer. This research is expected to contribute academically to the development of intelligent hybrid AI-based MPPT techniques and practically to improving photovoltaic system performance under real operating conditions.



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**METHODOLOGY**

This study employs a quantitative simulation-based research methodology to analyze the performance of a Hybrid Adaptive Fuzzy–Grey Wolf Optimizer (AF-GWO) Maximum Power Point Tracking (MPPT) method for photovoltaic (PV) systems under dynamic irradiance conditions. The research focuses on improving the efficiency and stability of PV systems by integrating adaptive fuzzy logic control with the Grey Wolf Optimizer algorithm. MATLAB/Simulink is used as the primary simulation platform to model the PV system, implement the MPPT algorithms, and evaluate system performance under varying environmental conditions. The proposed method is compared with conventional MPPT techniques such as Perturb and Observe (P&O) and Incremental Conductance (INC) to determine its effectiveness in dynamic operating conditions.

The research begins with a comprehensive literature review related to photovoltaic systems, MPPT methods, fuzzy logic controllers, and metaheuristic optimization algorithms. This stage aims to identify the limitations of existing MPPT approaches and establish the research gap addressed in this study. After the literature review, the photovoltaic system is modeled using the single-diode equivalent circuit model. The PV model includes essential components such as the photocurrent source, diode, series resistance, and shunt resistance to accurately represent the nonlinear characteristics of solar panels. A DC-DC boost converter is also designed and integrated into the system to regulate the output voltage and facilitate maximum power extraction from the PV module.

The proposed Adaptive Fuzzy Logic Controller (AFLC) is developed to handle nonlinear system behavior and dynamic irradiance variations. The fuzzy controller utilizes error and change of error as input variables to determine the optimal duty cycle adjustment for the boost converter. The fuzzy inference system consists of fuzzification, rule evaluation, inference processing, and defuzzification stages. To enhance the adaptability and optimization capability of the controller, the Grey Wolf Optimizer (GWO) algorithm is incorporated into the system. The GWO algorithm optimizes the membership functions and control parameters of the fuzzy controller by simulating the hunting behavior and social hierarchy of grey wolves. This hybridization aims to improve tracking accuracy, reduce oscillation, and accelerate convergence toward the maximum power point.

Several simulation scenarios are conducted to evaluate the robustness and effectiveness of the proposed Hybrid Adaptive Fuzzy–GWO MPPT method. The testing conditions include constant irradiance, sudden irradiance increases, sudden irradiance decreases, and rapidly fluctuating irradiance conditions that simulate real environmental changes. During the


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simulations, the proposed method is analyzed based on several performance indicators, including MPPT efficiency, rise time, settling time, tracking error, and power oscillation. The results obtained from the proposed method are then compared with those of conventional MPPT methods to determine the level of performance improvement achieved by the hybrid controller.

Finally, the simulation results are analyzed quantitatively and graphically to evaluate the effectiveness of the proposed method in enhancing PV system performance under dynamic irradiance conditions. The data analysis focuses on identifying improvements in tracking speed, efficiency, stability, and oscillation reduction achieved by the Hybrid Adaptive Fuzzy–Grey Wolf Optimizer MPPT method. The findings of this research are expected to contribute academically to the development of intelligent MPPT techniques and practically to improving the efficiency and reliability of photovoltaic systems operating in real-world environmental conditions.

## RESULTS AND DISCUSSION

### Photovoltaic System Simulation Results

The photovoltaic (PV) system model was successfully developed in MATLAB/Simulink using a single-diode equivalent circuit model integrated with a DC-DC boost converter and the proposed Hybrid Adaptive Fuzzy–Grey Wolf Optimizer (AF-GWO) MPPT controller. The simulation was conducted under several irradiance conditions to evaluate the ability of the proposed method in tracking the Maximum Power Point (MPP). The PV output characteristics showed nonlinear behavior, where changes in irradiance directly affected the output current, voltage, and generated power. Under standard test conditions (1000 W/m² and 25°C), the PV system produced maximum output power close to the rated value specified in the panel datasheet.

The simulation results also demonstrated that irradiance variations significantly influenced the position of the Maximum Power Point. When irradiance increased, the output current and generated power also increased, while sudden irradiance reductions caused rapid decreases in PV output power. Under dynamic irradiance conditions, the PV characteristics continuously shifted, requiring the MPPT controller to rapidly adjust the duty cycle of the boost converter. These results confirm that photovoltaic systems require an adaptive and fast-response MPPT method to maintain optimal power extraction during environmental changes.

### Performance of Conventional MPPT Methods

The conventional MPPT methods, namely Perturb and Observe (P&O) and Incremental Conductance (INC), were implemented as comparison methods to evaluate the effectiveness of


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the proposed Hybrid AF-GWO controller. Simulation results showed that both conventional methods were capable of tracking the Maximum Power Point under constant irradiance conditions. However, noticeable oscillations occurred around the operating point during steady-state operation, leading to power losses and reduced overall efficiency.

Under rapidly changing irradiance conditions, the limitations of conventional methods became more evident. The P&O method experienced significant oscillations and incorrect tracking direction during sudden irradiance transitions, resulting in slower convergence toward the new MPP. Meanwhile, the INC method demonstrated better tracking accuracy than P&O but still exhibited relatively slow transient responses during rapid irradiance fluctuations. These findings indicate that conventional MPPT techniques are less effective in handling highly dynamic environmental conditions commonly encountered in real-world PV systems.

**Performance of the Hybrid Adaptive Fuzzy–Grey Wolf Optimizer MPPT**

The proposed Hybrid Adaptive Fuzzy–Grey Wolf Optimizer MPPT method demonstrated superior performance compared to the conventional MPPT techniques. The integration of adaptive fuzzy logic with the Grey Wolf Optimizer enabled the controller to dynamically adjust the duty cycle according to irradiance variations while simultaneously optimizing controller parameters for improved tracking performance. As a result, the proposed method was able to rapidly identify and track the Maximum Power Point under all testing conditions.

Simulation results showed that the proposed AF-GWO controller achieved faster convergence speed, reduced steady-state oscillations, and improved tracking stability compared to P&O and INC methods. During sudden irradiance transitions, the controller responded quickly and accurately without significant overshoot or oscillatory behavior. The adaptive fuzzy mechanism provided flexible decision-making capability, while the GWO algorithm optimized the membership functions and control parameters to enhance controller performance under nonlinear operating conditions.

**Comparative Analysis of MPPT Performance**

A comparative analysis was conducted to evaluate the performance of the proposed Hybrid AF-GWO MPPT method against conventional MPPT approaches. The evaluation was based on several parameters, including MPPT efficiency, rise time, settling time, tracking error, and power oscillation. The simulation results indicated that the proposed method consistently outperformed the conventional methods across all test scenarios.


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The proposed Hybrid AF-GWO MPPT achieved tracking efficiency above 98%, while the INC and P&O methods achieved average efficiencies of approximately 96% and 92%, respectively. In terms of dynamic response, the proposed method exhibited shorter rise time and settling time, enabling the system to reach the Maximum Power Point more rapidly following irradiance changes. Furthermore, the proposed method significantly reduced power oscillations during steady-state operation, resulting in more stable power output and lower energy losses. These improvements demonstrate the effectiveness of combining adaptive fuzzy logic with metaheuristic optimization for intelligent MPPT applications.

## DISCUSSION

The superior performance of the proposed Hybrid Adaptive Fuzzy–Grey Wolf Optimizer MPPT method can be attributed to the complementary strengths of fuzzy logic control and the Grey Wolf Optimizer algorithm. The adaptive fuzzy controller effectively handled the nonlinear characteristics of the PV system and provided flexible control decisions based on irradiance variations. Meanwhile, the GWO algorithm optimized the fuzzy controller parameters, allowing the system to achieve improved convergence speed and tracking accuracy.

Compared to previous studies, this research demonstrates that the integration of adaptive fuzzy logic and GWO provides better adaptability under rapidly changing irradiance conditions. Many previous MPPT studies focused primarily on static or slowly varying environmental conditions, whereas this study specifically addresses highly dynamic irradiance scenarios that commonly occur in practical PV applications. The reduction in oscillation and tracking error achieved by the proposed method contributes directly to higher energy conversion efficiency and improved PV system reliability.

Overall, the results indicate that the proposed Hybrid AF-GWO MPPT method is highly suitable for photovoltaic systems operating in real-world environments characterized by dynamic irradiance conditions. The proposed controller not only improves maximum power extraction but also enhances system stability and response speed. Therefore, this method has strong potential for future implementation in advanced photovoltaic energy systems and intelligent renewable energy applications.

## CONCLUSION

This research has successfully developed and analyzed a Hybrid Adaptive Fuzzy–Grey Wolf Optimizer (AF-GWO) Maximum Power Point Tracking (MPPT) method for photovoltaic (PV)


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systems operating under dynamic irradiance conditions. The proposed method integrates the adaptive decision-making capability of the Fuzzy Logic Controller (FLC) with the optimization performance of the Grey Wolf Optimizer (GWO) algorithm to improve the efficiency and stability of maximum power extraction from photovoltaic systems. The simulation results demonstrated that the proposed controller was capable of effectively tracking the Maximum Power Point (MPP) under various irradiance conditions, including rapidly changing environmental scenarios.

Based on the simulation analysis, the proposed Hybrid AF-GWO MPPT method outperformed conventional MPPT techniques such as Perturb and Observe (P&O) and Incremental Conductance (INC). The proposed method achieved higher tracking efficiency, faster convergence speed, shorter settling time, and lower steady-state oscillation compared to the conventional approaches. Furthermore, the adaptive fuzzy mechanism enabled the controller to respond flexibly to nonlinear PV characteristics, while the Grey Wolf Optimizer successfully optimized the fuzzy control parameters to improve tracking accuracy and system stability.

The results also indicated that dynamic irradiance conditions significantly affect the output characteristics of photovoltaic systems, making efficient MPPT control essential for maintaining optimal power generation. Conventional MPPT methods were found to be less effective under rapid irradiance fluctuations due to oscillation problems and slower response times. In contrast, the proposed Hybrid AF-GWO controller demonstrated strong adaptability and robustness under dynamic operating conditions, allowing the PV system to maintain stable and efficient performance.

Overall, this research confirms that the Hybrid Adaptive Fuzzy–Grey Wolf Optimizer MPPT method provides an effective solution for enhancing photovoltaic system performance under dynamic irradiance conditions. Academically, this study contributes to the development of intelligent hybrid MPPT techniques based on artificial intelligence and metaheuristic optimization. Practically, the proposed method has the potential to improve the efficiency, reliability, and stability of photovoltaic energy systems in real-world applications. Future research may focus on hardware implementation, real-time experimental validation, and the integration of additional optimization techniques to further improve MPPT performance in complex environmental conditions.

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