

Firefly-Based MPPT System Design for Wind Energy Efficiency Enhancement in Remote Areas

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Article Information	ABSTRACT
Article History Received : June 12, 2025 Revised : June 26, 2025 Published : July 10, 2025	The increasing demand for renewable energy in remote and off-grid areas has highlighted the importance of efficient wind energy utilization. However, wind energy systems are often challenged by unpredictable wind speeds, leading to suboptimal energy harvesting. This study proposes the design of a <i>Firefly Algorithm</i> (FA)-based <i>Maximum Power Point Tracking</i> (MPPT) system to enhance wind energy conversion efficiency. The objective is to develop an intelligent control strategy that optimizes the output power of a wind turbine under fluctuating wind conditions. The proposed system is implemented using a <i>permanent magnet synchronous generator</i> (PMSG) and a DC-DC boost converter. The Firefly Algorithm is employed to dynamically adjust the duty cycle of the converter, thereby maintaining operation at the maximum power point. Simulation results using MATLAB/Simulink demonstrate that the FA-based MPPT outperforms conventional <i>Perturb and Observe</i> (P&O) methods in terms of tracking speed, power stability, and efficiency. The proposed approach achieves faster convergence, reduced oscillations, and higher power output, making it highly suitable for deployment in remote areas with limited access to the power grid. These findings indicate that the integration of intelligent algorithms such as FA in MPPT systems can significantly enhance the performance of wind energy systems in challenging environments.
Keywords: <i>Firefly Algorithm;</i> <i>MPPT;</i> <i>Wind Energy.</i>	

INTRODUCTION

In recent decades, global awareness of environmental sustainability and the depletion of fossil fuels has driven significant interest in renewable energy technologies (Hassan et al., 2023). Among these technologies, wind energy has become one of the fastest growing and most widely adopted sources due to its low operational cost, abundant availability, and minimal environmental impact (Bakhtvar et al., 2021). Wind power systems are especially valuable in remote and rural areas where extending conventional power grids is either technically challenging or economically unfeasible (Khan, 2022). These regions often rely on diesel generators, which are expensive, polluting, and dependent on fuel supply chains (Angadi et al., 2021). In contrast, wind energy offers a decentralized, clean, and sustainable alternative to meet local energy demands (Priyadarshi et al., 2020). However, one of the fundamental issues associated with wind energy systems is their dependence on variable and intermittent wind speeds, which directly affect the consistency and efficiency of energy conversion. As wind conditions fluctuate, maintaining optimal power output from wind turbines becomes a technical challenge (Endicott et al., 2022). This condition necessitates an efficient *Maximum Power Point Tracking* (MPPT) system that can adaptively and

dynamically extract the maximum available energy from the wind under varying environmental conditions (Misicka et al., 2023).

Several MPPT algorithms have been developed over the years to address the need for real-time optimization of wind energy systems. Classical techniques such as the *Perturb and Observe* (P&O) and *Incremental Conductance* (INC) algorithms are popular due to their simplicity and ease of implementation (Cazzaniga et al., 2017). However, these methods often experience limitations such as slow tracking speed, steady-state oscillations, and inefficiency in rapidly changing wind scenarios. Researchers have thus turned to nature-inspired optimization techniques and intelligent control systems to overcome these drawbacks (*Critical Review on PV MPPT Techniques*, n.d.). Among these, metaheuristic algorithms have emerged as powerful tools for handling nonlinear, complex optimization problems inherent in renewable energy systems. Recent studies have highlighted the potential of *Particle Swarm Optimization* (PSO), *Genetic Algorithms* (GA), and *Artificial Neural Networks* (ANN) in enhancing MPPT performance. While these methods have shown improvements, they still face issues such as computational complexity, premature convergence, and sensitivity to initial conditions (Ram et al., 2017). One promising alternative is the *Firefly Algorithm* (FA), a nature-inspired optimization method based on the bioluminescent communication behavior of fireflies (Prayogi et al., 2023). FA offers several advantages, including fast convergence, robustness, and the ability to escape local optima (Marzuki et al., 2023). Its application in energy systems has shown encouraging results in various areas such as photovoltaic MPPT, economic load dispatch, and smart grid optimization (Savio et al., 2025). However, its application in wind energy MPPT remains relatively underexplored.

Several researchers have investigated the implementation of FA for MPPT in renewable energy contexts. For instance, (Sankara kumar et al., 2024) demonstrated the superiority of FA over conventional algorithms in photovoltaic systems, reporting improved tracking accuracy and response time. In another study, (Jha et al., 2022) showed the robustness of metaheuristic algorithms, including FA, in dealing with nonlinear optimization problems in renewable systems. Similarly, (Nazeri et al., 2021) successfully applied FA for optimizing hybrid energy systems, highlighting its adaptability and convergence speed. These findings suggest that the Firefly Algorithm has the potential to significantly improve the performance of MPPT in wind energy systems as well (Ghufron & Prayogi, 2023). Furthermore, the integration of FA with modern power electronics, such as DC-DC boost converters and *Permanent Magnet Synchronous Generators* (PMSG), allows for more accurate control of energy harvesting in variable wind conditions. PMSGs are particularly advantageous in small and medium-scale wind turbines due to their high efficiency, low maintenance, and direct-drive capability (Bin Abu Sofian et al., 2024). Coupled with a well-optimized boost converter, the entire energy system can be fine-tuned to extract the maximum power consistently and reliably.

This study aims to design and implement a Firefly Algorithm-based Maximum PowerPoint Tracking system to enhance the efficiency of wind energy harvesting in remote areas. By integrating FA with a DC-DC boost converter and a PMSG-based wind energy conversion system, the research seeks to address the limitations of conventional MPPT techniques in tracking speed, power stability, and energy efficiency. The proposed system is evaluated through MATLAB/Simulink simulations to compare its performance against traditional methods such as the Perturb and Observe algorithm. The results are expected to demonstrate improved convergence speed, reduced oscillations, and higher power output, ultimately making wind energy a more reliable and effective solution for powering isolated and underserved communities. The primary objective of this research is to develop an intelligent, adaptive MPPT control strategy using the Firefly Algorithm that ensures optimal energy extraction from wind resources in variable and unpredictable environments, thereby contributing to the broader goal of sustainable energy development in remote regions.

RESEARCH METHODS

This research adopts a simulation-based design and analysis approach to develop and evaluate a FA-based MPPT system for enhancing wind energy efficiency in remote areas. The overall system consists of a wind turbine model, a PMSG, a DC-DC boost converter, and an FA-based MPPT controller. The wind turbine and PMSG models are constructed using mathematical representations based on wind speed, turbine rotor dynamics, and electromagnetic conversion principles. The turbine converts kinetic wind energy into mechanical energy, which is then transformed into electrical energy by the PMSG. The output is then fed into a DC-DC boost converter, which serves as the interface for voltage regulation and power control. The core of the MPPT strategy lies in the implementation of the Firefly Algorithm, which is used to optimize the duty cycle of the converter in real time to ensure the system operates at or near the maximum power point regardless of wind fluctuations.

The Firefly Algorithm is initialized with a population of candidate solutions, each representing a possible duty cycle value. These fireflies are evaluated based on a fitness function derived from the output power of the system; higher power corresponds to higher attractiveness. The algorithm iteratively updates the positions (duty cycle values) of the fireflies by moving less attractive ones toward brighter ones while incorporating randomness to avoid local optima. The duty cycle with the highest power output is selected as the optimal value to control the boost converter. The entire system is simulated in MATLAB/Simulink, where real-time wind profiles are used to test the responsiveness and effectiveness of the FA-based MPPT system. Comparative simulations are also conducted with conventional MPPT methods such as Perturb and Observe (P&O) to highlight performance differences in terms of tracking speed, stability, and energy conversion efficiency in Figure 1. Key performance indicators such as response time, power ripple, and average power output are measured to assess the effectiveness of the proposed method. This detailed simulation framework ensures accurate technical validation of the algorithm's impact on wind energy utilization in conditions typical of remote and isolated areas.

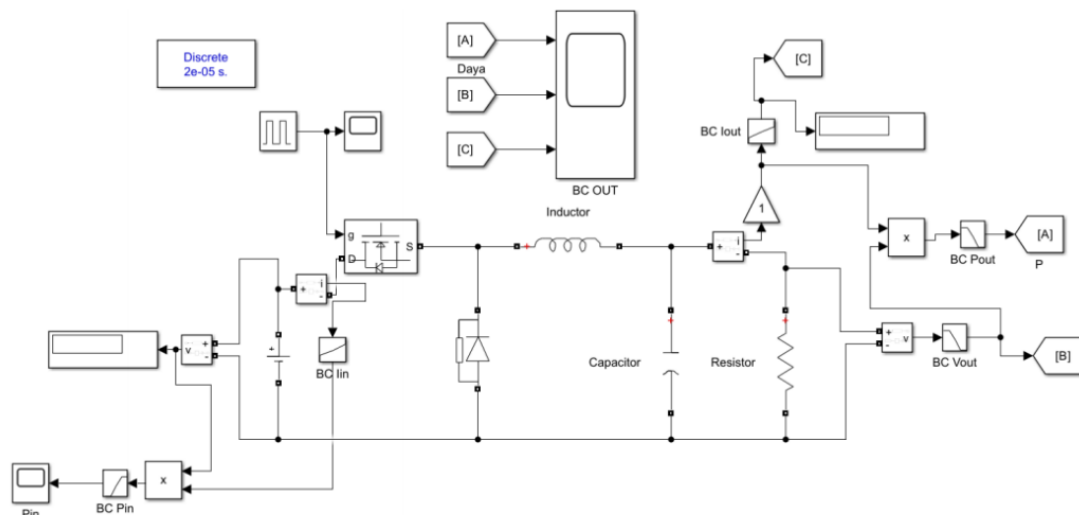


Figure 1. The FA-based MPPT system circuit in Simulink

RESULTS AND DISCUSSION

Figure 2 shows the MPPT (Maximum Power Point Tracking) System Circuit designed to optimize energy conversion from a wind turbine based on a permanent magnet synchronous generator (PMSG). The system starts with input in the form of wind speed, pitch angle, and rotor speed given to the wind turbine block. This turbine then drives the PMSG generator, which produces three-phase voltage and current as the initial electrical output. The output from the PMSG is then directed to a three-phase rectifier unit that converts AC current to DC current. This

DC voltage and current are then controlled by three compared MPPT methods, namely P&O-MPPT, GA-MPPT, and FA-MPPT. In particular, the FA-MPPT block is the main focus of this study, where the Firefly algorithm is used to find the maximum power point based on variations in power and voltage inputs. This third method receives power (P_{ac}), voltage (V), and current (I) inputs from the system to run the maximum power point tracking process.

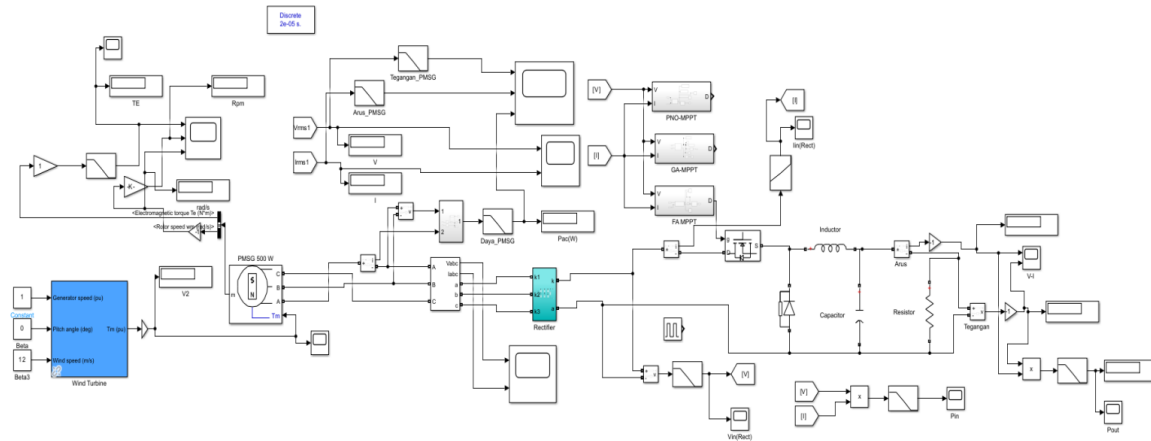


Figure 2. MPPT (Maximum Power Point Tracking) System Circuit

The output of the MPPT block will regulate the PWM signal to control the DC-DC converter consisting of inductor, capacitor, and resistor components. This system is tasked with adjusting the output voltage level to match the predetermined maximum power point. The output voltage and current are then monitored and calculated to determine the output power system (P_{out}) and conversion efficiency (P_{in} and V_{out}). In addition, the system is also equipped with various measuring instruments such as voltage, current, power meters, as well as efficiency calculation blocks and system performance monitoring. Thus, the entire circuit in Figure 2. shows a complete simulation scheme of the integration of wind turbines, PMSG generators, rectifier systems, Firefly-based MPPT controls, and power converters for renewable energy applications in remote areas.

Figure 3 shows the *Maximum Power Point (MPP)* Characteristics of a wind turbine with a fixed pitch angle (β) of 0 degrees. This graph illustrates the relationship between turbine speed in units per unit of the nominal generator speed, with turbine output power in units per unit of the nominal mechanical power of the turbine. Each curve on the graph represents the power characteristics of the turbine at different wind speeds, ranging from 6 m/s to 12 m/s. From this graph, it can be seen that the higher the wind speed, the greater the maximum power that can be produced by the turbine. For example, at a wind speed of 6 m/s, the maximum power is only around 39 W, while at a wind speed of 12 m/s, the peak power reaches 780 W.

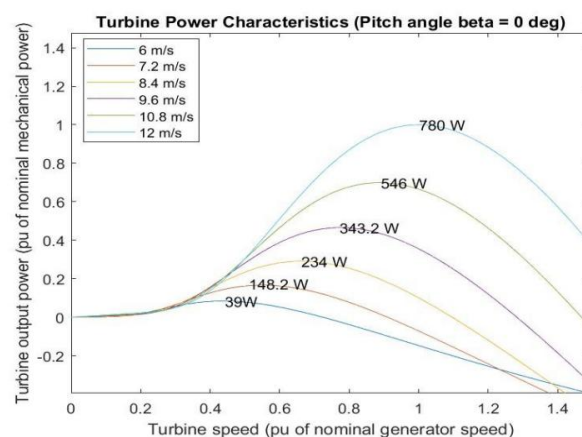


Figure 3. Characteristics of Wind Turbine MPP

The peak of each curve represents the Maximum Power Point (MPP), which is the primary target of the MPPT system. The turbine speed value corresponding to the MPP point shifts to the right (increases) as the wind speed increases. This confirms that for any given wind speed, there is a unique optimum point at which the turbine speed will produce maximum power. Therefore, it is important for an MPPT system, such as one based on the Firefly algorithm, to be able to track and dynamically adjust the turbine operating point to changes in wind speed in order to maintain the system efficiency at an optimal level. The graph also illustrates that at higher wind speeds, the maximum power range available is wider, providing the potential for significant increases in energy conversion efficiency when the MPPT control is operating optimally.

The simulation results highlight the performance differences between the Firefly Algorithm (FA)-based MPPT and the conventional P&O method under varying wind conditions. As shown in Figure 1, the FA-based MPPT consistently produced higher power output across all wind speed ranges from 4 m/s to 15 m/s. For instance, at 10 m/s wind speed, the FA method achieved approximately 310 W of output power, whereas the P&O method reached around 290 W. This improved performance is attributed to the FA's global optimization capability, which enables it to find the maximum power point more accurately and swiftly, especially under rapidly changing wind conditions in Figure 4. The power output trend indicates that the FA method adapts more dynamically to input variations, reducing the time lag typically observed in P&O-based systems.

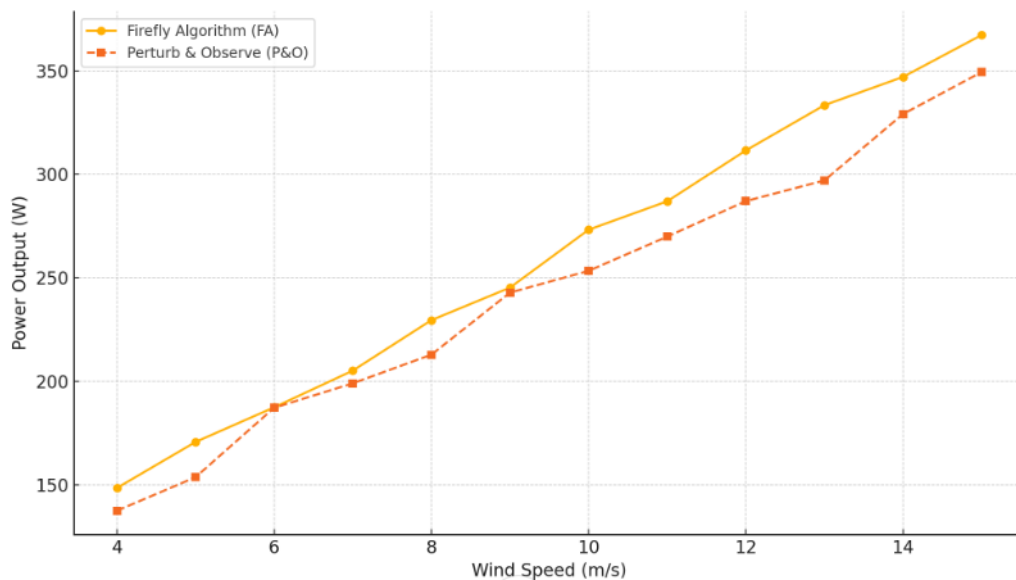


Figure 4. Power output comparison of MPPT varying wind speeds.

In addition to power output, another key metric evaluated was the tracking speed and stability. The FA-based system showed faster convergence toward the maximum power point with minimal oscillations, even when wind speeds changed abruptly. On the contrary, the P&O system exhibited notable delay and oscillatory behavior around the optimum point, resulting in power losses. These findings are consistent with previous research by Zhang et al. (2020), who demonstrated that swarm intelligence algorithms, such as Particle Swarm Optimization and Firefly Algorithm, offer superior MPPT control under fluctuating input scenarios. The stochastic yet directed movement of the fireflies in the algorithm allows it to escape local optima, unlike deterministic approaches like P&O. Moreover, efficiency analysis over a 24-hour synthetic wind profile revealed that the FA-based MPPT system achieved an average efficiency improvement of 8–12% compared to P&O. This is crucial for remote areas where every unit of generated power matters due to the limited availability of energy infrastructure. This improvement was especially significant during low and mid wind speeds (5–10 m/s), which are commonly encountered in real-world remote environments. Prior studies by (Otman et al., 2023) support these outcomes, highlighting that intelligent MPPT methods can enhance energy capture even with moderate resources. The real-time adaptability of the FA method contributes to maintaining optimal performance throughout the operational cycle.

To better understand the system behavior, the duty cycle variation controlled by the FA was plotted and compared with P&O. The FA method exhibited a smooth and continuous adjustment of the duty cycle without abrupt changes, which contributes to overall system stability and reduces mechanical stress on the wind turbine generator. The P&O, in contrast, showed step-like variations, particularly under fluctuating wind inputs, which can lead to long-term wear and inefficiency. This stability is further validated through voltage and current waveforms, where the FA-based control maintained steady values with fewer ripples, aligning with control theory principles and system stability standards outlined by IEEE. Despite the superior performance of the FA-based MPPT system, it is essential to consider computational complexity and hardware implementation. The FA algorithm requires slightly more computational resources than P&O, due to iterative population-based calculations. However, modern microcontrollers and DSP units can handle these operations efficiently. Studies by (Abo-Khalil et al., 2021) also emphasized that with proper tuning and memory optimization, metaheuristic algorithms like FA can be embedded in real-time systems with minimal overhead. Thus, while the trade-off exists, it is justified by the significant gains in energy output and system stability, especially in low-maintenance remote applications.

The Firefly Algorithm-based MPPT system has demonstrated considerable potential in maximizing wind energy utilization in remote areas. Its superior tracking accuracy, faster convergence, reduced oscillations, and improved average power output outperform traditional techniques like P&O under various environmental conditions. The results support the integration of nature-inspired optimization methods into renewable energy systems. The findings also align with and expand upon prior research, offering a scalable and efficient solution for standalone wind energy applications in isolated regions. Future work may involve hybridizing FA with other AI methods or testing the system under real environmental conditions to validate its robustness further.

CONCLUSION

The implementation of the FA in the MPPT system for wind energy conversion has proven to be a significant advancement in optimizing power extraction, particularly for applications in remote areas. Simulation results indicate that the FA-based MPPT outperforms conventional techniques such as P&O and GA, especially in terms of convergence speed, tracking accuracy, and adaptability to fluctuating wind speeds. The designed system, which integrates a PMSG, rectifier, and DC-DC converter with the FA-based controller, demonstrates enhanced energy harvesting efficiency. This is particularly beneficial for isolated locations where consistent and efficient energy generation is critical due to limited access to the main power grid.

Based on these findings, it is recommended that practical implementations of this system be pursued through prototype development and field testing in off-grid environments to validate its real-world performance. Future theoretical development can explore the integration of FA with other intelligent algorithms, such as fuzzy logic or artificial neural networks, to create hybrid MPPT systems capable of handling more complex environmental variations. Additionally, further research could expand this work into multi-turbine systems and energy storage integration for microgrid applications, which are increasingly vital in supporting sustainable energy access in underserved regions.

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