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Optimized ANFIS-Based Control of Variable-Speed Wind Turbines Using Bayesian Optimization for Enhanced Efficiency and Adaptability

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Abstract

Variable-speed wind turbines are important for achieving better energy efficiency and reducing mechanical wear in changing wind conditions. This research improves the Adaptive Neuro-Fuzzy Inference System (ANFIS) used for controlling these turbines by proposing a new approach for tuning hyperparameters with Bayesian Optimization. The method searches the hyperparameter space dynamically, helping to optimize fuzzy membership functions and training parameters. This improves the model's accuracy while also lowering computational effort. Simulations in MATLAB show that the optimized ANFIS achieves more power output and smoother control compared to traditional methods under varying wind speeds. Results indicate that turbine efficiency is significantly increased, with a 15% reduction in mean squared error (MSE), and the system adapts better to real-time changes in wind conditions. These findings highlight the potential of combining Bayesian Optimization with ANFIS for improving wind energy systems.

Keywords: Wind Turbine Control, Adaptive Neuro-Fuzzy Inference System, Bayesian Optimization, Renewable Energy

1. Introduction

The worldwide movement towards renewable energy has led to notable progress in wind energy technologies. Wind turbines play a key role in this transition by transforming wind's kinetic energy into mechanical and electrical power. Yet, optimizing their performance amid changing wind conditions remains a significant challenge. Traditional fixed-speed wind turbines struggle to adjust to varying wind speeds, leading to lower energy efficiency and higher mechanical stress on parts. In contrast, Variable Speed Wind Turbines (VSWTs) offer a solution by modifying rotor speed to enhance power output and reduce stress. However, VSWTs need strong control systems to manage complex nonlinear dynamics and unpredictable wind patterns (Xu, 2024).

Over time, various control methods for wind turbines have been developed to improve precision and reliability. Adaptive Neuro-Fuzzy Inference Systems (ANFIS) have gained attention for combining neural networks' learning abilities with fuzzy logic's interpretability. ANFIS is effective in modeling nonlinear systems and adapting to environmental changes. Its use in wind turbine control has shown positive results, especially in boosting power output and lowering mechanical stress through dynamic parameter adjustments (Ghobakhloo et al., 2022; Nilashi et al., 2015).

Despite these benefits, ANFIS's performance largely depends on choosing the right hyperparameters, like the number and type of fuzzy membership functions, learning rates, and training epochs. Traditional tuning methods, such as grid search or manual adjustments, are time-consuming and may not effectively explore the extensive hyperparameter space, potentially leading to less optimal performance and inefficiency. To overcome this, an intelligent optimization approach is necessary (Guerra et al., 2024).

Bayesian Optimization has become a strong method for hyperparameter tuning in machine learning and control systems. By viewing the hyperparameter search as a probabilistic model, it iteratively selects parameters that maximize a specific function, balancing exploration and exploitation. Unlike traditional methods, Bayesian Optimization can find the best configuration with fewer evaluations, making it suitable for complex applications like ANFIS (Al Hadi & Aly, 2024).

Numerous studies have explored the application of Adaptive Neuro-Fuzzy Inference Systems (ANFIS) in the domain of wind turbine control, underlining its adaptability and effectiveness. For instance, (Cahyadi et al., 2024) examined the integration of ANFIS for controlling the blade pitch angle in wind turbines. Their work, using a comprehensive simulation framework, validated the system's ability to adapt to varying wind speeds, demonstrating enhanced control precision and stability in fluctuating conditions. Similarly, (Fazlollahi et al., 2019) investigated the modeling and validation of variable-speed