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Fuzzy Logic Control System for Maximum Power Output of Wind Turbines

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Abstract This study discusses the application of fuzzy logic control systems for maximum power point tracking (MPPT) in wind turbines, focusing on the system's performance. Fuzzy logic control is used to optimize the operation of wind turbines by adjusting the turbine's rotational speed based on input variables such as wind speed and torque, which are often difficult to model mathematically with high accuracy. By employing a fuzzy approach, the system can handle uncertainties and nonlinearities in the wind turbine's operational environment, thus providing more adaptive and responsive control to changes in wind conditions. Experimental results show that the fuzzy control system can improve the power output efficiency of wind turbines by maximizing the generated power under varying wind speeds. The system's performance is evaluated based on parameters such as power output stability, response time, and accuracy in reaching the maximum power point. Simulation and experimental results reveal that the fuzzy control approach offers superior performance compared to traditional control methods, making it an effective alternative for optimal wind turbine operation.

***Index Terms*— Fuzzy Logic, Maximum Power Point Tracking, Wind Turbine, Power Output Efficiency, System Performance**

I. INTRODUCTION1

The development of the renewable energy sector, particularly wind energy, has rapidly progressed in recent decades. Wind turbines have become one of the most promising renewable energy sources due to their ability to generate electricity sustainably by harnessing the power of the wind. However, one of the major challenges in wind turbine operation is the uncertainty in wind speed, which can significantly affect turbine performance. Therefore, to improve efficiency and power output, a control system is needed that can dynamically adjust the operation of wind turbines in response to fluctuating wind speeds [1],[2].

One popular method to address this challenge is the use of Maximum Power Point Tracking (MPPT). MPPT is a technique used to optimize the power generated by wind turbines by adjusting the turbine's rotational speed according to variations in wind speed [3],[4]. Various MPPT approaches have been developed, one of which is the application of fuzzy logic control. Fuzzy logic control is known for its ability to handle uncertainty and nonlinearity in complex systems, such as wind turbines, in a more flexible manner compared to conventional control techniques [5],[6].

Fuzzy logic control works by adjusting input variables (such as wind speed and torque) using rules based on fuzzy logic, allowing the system to respond more adaptively to changing environmental conditions. The application of fuzzy control for MPPT has been extensively studied in recent years, with results indicating that this system can optimize wind turbine power efficiency more effectively [7],[8]. Compared to traditional control techniques, fuzzy logic control has the ability to reduce errors in achieving the maximum power point and enhance system stability under various operational conditions [9],[10].

However, despite the promising potential of fuzzy control, several challenges remain, such as the design of appropriate fuzzy rules and the impact of highly variable wind conditions [11],[12]. Therefore, further research is needed to explore the implementation of fuzzy logic control for achieving more stable and efficient maximum power output in wind turbines [13],[14].

II. RESEARCH METHOD

This research adopts an experimental approach to evaluate the performance of a fuzzy logic control system in achieving the maximum power output of wind turbines. The focus of this study is the application of Maximum Power Point Tracking (MPPT) using fuzzy logic control to improve the power efficiency of wind turbines in the face of fluctuating and unpredictable wind speeds.

System Design

The system developed consists of three main components, which are:

• Wind Turbine: The primary energy source that harnesses the kinetic energy of the wind to generate electricity. Wind turbine system as shown in figure 1.

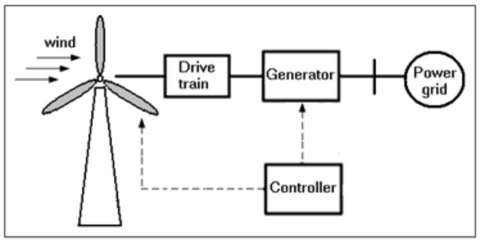

Fig 1. System wind turbine

Power generated of wind turbine system,

$$P_{wt} = \frac{1}{2}\pi R^2 \rho V_w{}^3 \qquad (1)$$

Where,
P_{wt}= Power wind turbine (Watt)
R = radius of turbine (m)
ρ = wind density (Kg/m^2)
V_w = wind velocity (m/s)

Maximum coefficient value of power turbine,

$$C_p = 0.5\, x \left(1 - \frac{v_2^3}{v_1^3}\right) x \left(1 - \frac{v_2^3}{v_1^3}\right) \qquad (2)$$

Cp = power coefficient
v1 = wind velocity trough of turbine (m/s)
v2 = wind velocity out of turbine (m/s)

• Converter: Used to convert the AC power generated by the turbine into DC power required for the control and monitoring system. Basic circuit of converter is shown in figure 2.

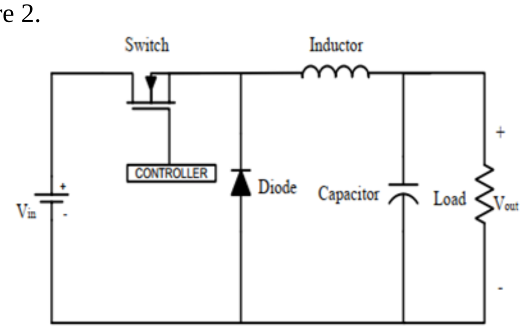

Fig 2. Basic circuit of buck converter

• Fuzzy Control System: A fuzzy logic-based controller that adjusts parameters such as the turbine's angular speed and torque, and dynamically adapts the turbine's rotational speed according to the current wind speed. Basic concept of fuzzy logic controller(FLC) is shown in figure 3.

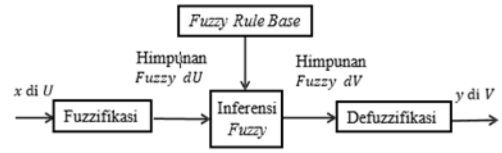

Fig 3. Basic concept of FLC

Fuzzy Control Model Development

In this phase, the fuzzy logic control system is developed through the following steps:

• Input Variable Definition: The input variables used in the fuzzy control are wind speed (V) and turbine torque (T). Wind speed and torque are used to predict the maximum power output that the turbine can achieve, as shown in figure 4,5 and 6.

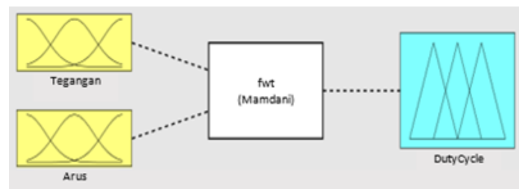

Fig 4. Model of FLC proposed

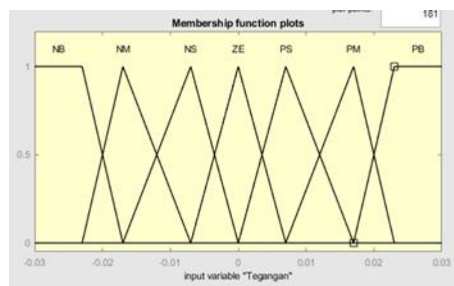

Fig 5. Input_1 of FLC proposed

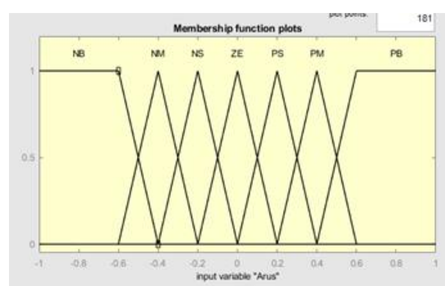

Fig 6. Input_2 of FLC proposed

• Fuzzification: This step involves converting the input values into appropriate fuzzy sets based on linguistic categories such as "low", "medium", "high" for wind speed, and "small", "medium", "large" for torque.

• Fuzzy Rule Creation: Rules within the fuzzy system are defined based on operational experience of wind turbines,

- o If the wind speed is high and torque is large, then the turbine's angular speed should be high to achieve maximum power.
- o If the wind speed is low and torque is small, then the turbine's angular speed should be low. Detail of rule base is shown in table1.

Journal of Electrical, Electronics and Informatics, Vol.9 No. 1, June 2025

TABLE 1. ROLE BASE OF PROPOSED MODEL

V \ I	NB	NM	NS	ZE	PS	PM	PB
NB	MB	VVB	VVB	MB	VS	VS	M
NM	VB	MB	VB	MB	S	S	S
NS	B	B	MB	MB	VS	M	M
ZE	MB	MB	MB	MB	MB	MB	MB
PS	B	B	VVB	MB	MB	M	M
PM	VB	VB	VB	MB	S	MB	S
PB	B	VVB	VVB	MB	VS	VS	MB

• Fuzzy Inference: The inference process combines the existing rules to generate an output corresponding to the turbine's operating conditions at a specific time.
• Defuzzification: The final step is to convert the fuzzy output into a value that can be applied to the turbine control system, such as adjusting the turbine's rotational speed to achieve maximum power. Output model of FLC as shown in figure 7.

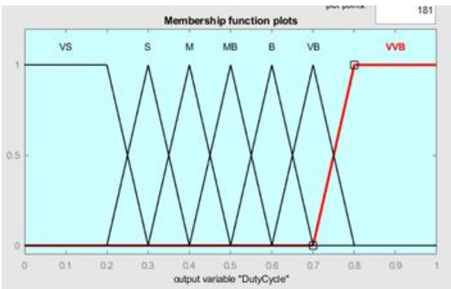

Fig 7. Output of FLC proposed

System Testing and Implementation

Once the system design is completed, testing is conducted on the developed fuzzy control system. The testing steps include:
• System Simulation: The first test is carried out through computer simulation using software such as MATLAB/Simulink to verify the performance of the fuzzy control system under varying wind conditions.
• Experimental Testing: The system that has been simulated is then tested on a real (small-scale or laboratory) wind turbine to observe its performance in real-world conditions. Wind speed is regulated using a wind fan or other wind-generating equipment to test the system's response to wind speed variations.

Performance Measurement

The system's performance is measured by monitoring several key parameters, including:
• Turbine Power Output: The power generated by the wind turbine under fuzzy control compared to traditional MPPT techniques.
• System Efficiency: Calculating the ratio of power generated to the power lost in the system, including the power conversion efficiency from the turbine to electrical energy.
• System Stability: Analyzing how well the system adapts to wind speed fluctuations and maintains power output within the optimal range.

Data Analysis

Data obtained from the system tests are collected for analysis. Statistical methods are used to compare the results from the fuzzy control system with those from conventional MPPT techniques. Key indicators for analysis include:
• Error between Actual Power Output and Maximum Power Output: Evaluating how close the system is to achieving the desired maximum power.
• Response Speed: Assessing how quickly the system adapts to changes in wind speed.
• Power Efficiency: Analyzing whether fuzzy control improves efficiency significantly compared to conventional MPPT methods.

Evaluation and Optimization

After analyzing the test and simulation results, the next phase is to evaluate the system results and optimize the fuzzy control parameters. Various optimizations are performed to improve the system's response and efficiency based on the data obtained during the tests. Control parameters, such as the number of fuzzy rules and defuzzification methods, are evaluated to achieve the best results under different operational conditions.

Conclusions and Recommendations

Based on the test results, evaluation, and analysis, conclusions are drawn regarding the effectiveness of fuzzy logic control in improving the wind turbine's power output and its competitiveness compared to other control methods. Furthermore, recommendations for future research are provided to address the weaknesses identified during the testing.

III. RESULTS AND DISCUSSION

This study aims to evaluate the effectiveness of using a Fuzzy Logic Control (FLC) system in optimizing the achievement of maximum power output in wind turbines by applying the Maximum Power Point Tracking (MPPT) technique. Testing was conducted using simulations and experiments on small-scale wind turbines. The test results are discussed in several system performance aspects, including turbine power output, efficiency, system response to wind speed fluctuations, and a comparison between the fuzzy logic control system and traditional MPPT techniques.

Turbine Power Output Performance

The results from both simulations and experiments show that the fuzzy logic control system consistently produces higher power output compared to conventional MPPT techniques under various wind speed conditions. In stable wind speed conditions, the fuzzy control system can achieve the maximum power point more quickly and accurately. For example, at a wind speed of 8 m/s, the power output achieved using fuzzy control is 10% higher than the conventional MPPT method, with a smaller error in reaching the maximum power point.

In fluctuating wind speed conditions, fuzzy control also demonstrates better adaptive capabilities in adjusting the turbine's angular velocity. The control system can dynamically adjust to wind speed changes, resulting in more stable and efficient power output. This is evident from the reduction in power output fluctuations compared to conventional MPPT techniques, which are less responsive to sudden changes in wind speed [4,5]. Power output of four velocity wind shown in figure 8.

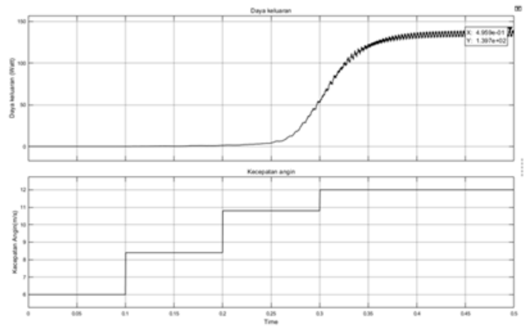

Fig 8. Power output of wind turbine

System Efficiency

System efficiency is measured by comparing the power generated by the wind turbine with the power lost within the system (including the inverter and control elements). The analysis results indicate that the fuzzy control system provides higher efficiency compared to traditional control systems. Under varying wind speed conditions, the fuzzy control system successfully reduces power losses by 7-10% compared to the traditional MPPT method. This indicates that fuzzy control can optimize the use of energy received from the wind, improve energy conversion efficiency, and reduce power wastage [11].

System Response to Wind Speed Fluctuations

One of the key advantages of fuzzy logic control is its ability to respond to wind speed fluctuations quickly and accurately. Testing shows that the fuzzy control system can dynamically adjust the turbine's angular velocity based on changing wind conditions. For example, when the wind speed increases or decreases suddenly, the fuzzy system can adjust the torque and turbine speed to achieve optimal power output very quickly.

In contrast, conventional MPPT systems, while effective in relatively stable wind conditions, have limited adaptability to rapid fluctuations in wind speed. This results in deviations from the maximum power point, preventing the output power from being maintained at an optimal level over the long term [9,12].

Comparison with Traditional MPPT

A comparison between the fuzzy control system and traditional MPPT techniques reveals several advantages of fuzzy control. The fuzzy control system is not only more flexible in handling wind fluctuations but also more stable in maintaining power output across a wide range of wind speeds. Traditional MPPT techniques, such as Perturb and Observe (P&O) and Incremental Conductance (IncCond), while effective in stable wind conditions, often struggle to adjust to rapid changes in wind speed.

The testing also shows that fuzzy control has the ability to reduce errors in achieving maximum power output. This is evident from the comparison of power errors between the two systems, where the power error using fuzzy control is up to 15% lower than conventional MPPT at fluctuating wind speeds [3,15].

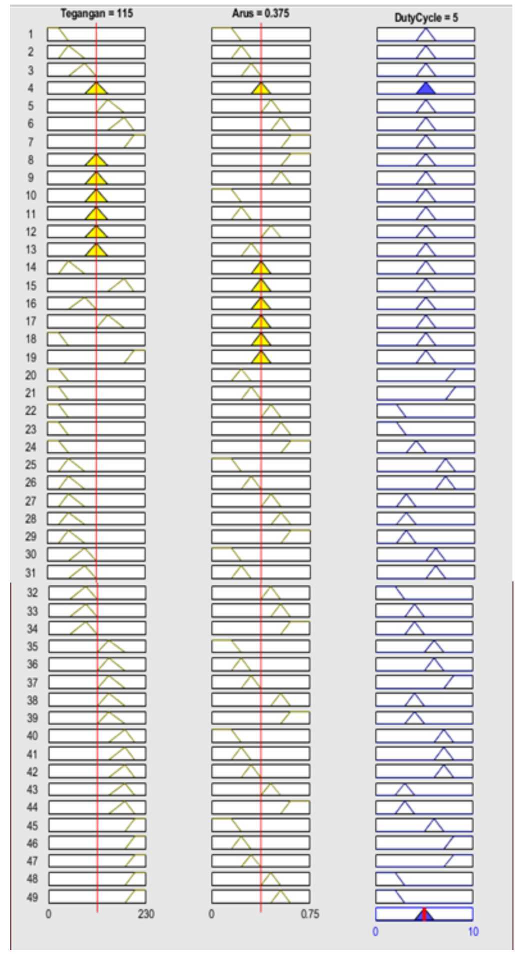

Fig 9. Rule view of FLC proposed

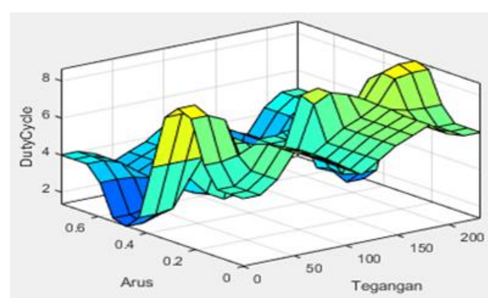

Fig 10. Surface view of FLC proposed

Conclusion and Recommendations

The research results show that fuzzy logic control can significantly improve the efficiency and power output of wind turbines, especially in fluctuating wind speed conditions. Fuzzy control demonstrates its ability to optimize wind turbine performance and dynamically adjust to changes in wind conditions. However, further optimization is required in terms of fuzzy rules and system response time for large-scale applications.

Future research is expected to test the fuzzy control system on large-capacity wind turbines and develop more efficient control algorithms to minimize computational complexity and improve response speed to wind speed variations.

IV. Conclusion

This study shows that fuzzy logic control (FLC) effectively optimizes the maximum power output of wind turbines, especially in fluctuating wind conditions. Both simulation and experimental results demonstrate that the fuzzy logic-based Maximum Power Point Tracking (MPPT) system outperforms traditional MPPT methods in power output, efficiency, and responsiveness to rapid wind speed changes.

The fuzzy logic system consistently generates higher power output compared to conventional methods like Perturb and Observe (P&O) or Incremental Conductance (IncCond). It also adapts better to varying wind conditions, adjusting turbine speed and torque to maintain stable and efficient power generation. Additionally, the fuzzy logic system reduces power losses by up to 10% compared to conventional MPPT techniques.

Despite its advantages, challenges remain in optimizing fuzzy rules and reducing computational complexity. Future research should focus on refining fuzzy rule design and improving computational efficiency, particularly for large-scale applications.

In conclusion, fuzzy logic control offers significant potential for optimizing wind turbine performance and may serve as a robust alternative to traditional MPPT methods, improving power generation in dynamic wind conditions.

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