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Comprehensive Analysis of Blade Design Parameters and its Influence on Performance of Micro Wind Turbine

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Abstract

Micro-wind turbines are crucial elements of distributed energy systems, especially in areas with moderate wind velocities. Their efficacy is significantly influenced by the aerodynamic and structural configuration of the blades. This paper presents a thorough analysis of the principal blade design parameters namely chord length, twist angle, airfoil selection, blade count, and solidity and their impact on turbine performance. Analytical equations are derived using the Blade Element Momentum (BEM) theory to model the influence of these parameters on performance metrics such as the power coefficient, starting torque, and cut-in speed. Computational Fluid Dynamics (CFD) simulations augment the theoretical analysis. This study enhances the design optimization of micro-wind turbines, providing actionable insights for future advancements.

Major Findings: *The results indicate that optimizing chord length and twist angle markedly improve energy capture and startup performance, while suitable airfoil selection guarantees operational efficiency at low Reynolds numbers.*

Keywords: *Blade Design Parameter, Drag Force, Lift Force, Micro Wind Turbine, Power Output*

1.0 Introduction

Micro-Wind Turbines (MWT) are small-scale wind energy systems engineered to generate electricity locally, providing a sustainable alternative in regions with moderate wind resources. Their capacity to produce clean energy locally renders them a crucial element of microgrids, enhancing energy sustainability and diminishing reliance on fossil fuels[1]. MWTs provide an environmentally sustainable alternative to conventional energy sources by diminishing greenhouse gas emissions, in accordance with global initiatives to advance green energy technologies[2]. MWTs are progressively incorporated into microgrids to improve energy reliability and effectively address local electricity demands[3].

The efficacy of wind turbines is affected by numerous essential factors. Factors including chord length, twist angle, and blade quantity directly influence the aerodynamic lift and drag forces on the rotor, thereby affecting energy capture and startup efficiency[4]. The quantity of blades influences energy output, as an increased number enhances torque and starting performance in low wind conditions[5]. Furthermore, parameters such as solidity (the ratio of blade area to swept area) enhance starting torque but may induce drag at elevated speeds, necessitating meticulous balancing to preserve efficiency[6]. The distribution of twist angle along the blade span preserves an optimal angle of attack, thereby improving aerodynamic efficiency and power output by aligning the blades with diverse wind flow conditions[4]. The

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design parameters collectively affect the efficiency, power coefficient, and energy output of micro-wind turbines. Recent studies on the design optimization of micro-wind turbines concentrate on enhancing aerodynamic efficiency via sophisticated blade geometries, airfoil selection, and computational models, thereby ensuring increased power output in low-wind scenarios. Bekkai *et al.*,[7] enhanced a micro-HAWT blade design through CFD and MOGA, realizing a 3.6% increase in efficiency by optimizing chord length and twist angle distribution. Abdelhalim *et al.*,[8] developed and prototyped compact wind turbine blades via 3D printing to capture low wind velocities in Algeria, enhancing aerodynamic and structural efficacy. Bourhis *et al.*,[9] established that augmenting blade solidity in micro-scale turbines improves power coefficient and postpones stall, thereby optimizing performance at low tip-speed ratios. Bourhis *et al.*,[10] discovered that augmenting the number of blades in micro-scale turbines enhances efficiency and lowers cut-in wind speed, with optimal performance attained at 12-14 blades. Arivalagan *et al.*,[11] engineered and refined 3D-printed PLA turbine blades utilizing MFO, resulting in enhanced structural performance for low-wind-speed applications.

This paper aims to examine the impact of critical blade design parameters namely chord length, twist angle, solidity, blade count, airfoil choice, and Reynolds number on the power output and overall efficacy of micro-wind turbines. This paper presents a comprehensive theoretical analysis of each parameter, substantiated by pertinent equations and contemporary literature. The discussion section analyzes the trade-offs inherent in design decisions, whereas the conclusion encapsulates principal findings and their implications for enhancing micro-wind turbine efficiency.

2.0 Blade Element Momentum (BEM) Theory

The Blade Element Momentum (BEM) theory is a technique employed to forecast the aerodynamic efficiency of micro-wind turbines by simulating the interaction between airflow and blade components. It integrates momentum theory and blade element theory to simulate the interaction of individual blade segments with the wind, accurately forecasting energy capture and performance. This method is essential for optimizing micro-wind turbines for practical applications, effectively balancing mechanical and aerodynamic efficiency.

2.1 Key concepts in BEM theory

2.1.1 Aerodynamic Forces on Blade Elements

The lift and drag forces generated on an individual blade element are calculated using Equation number 1 and 2 respectively.

Lift forces

$$F_L = \frac{1}{2}\rho V_r^2 c C_L$$

Equation No. 1: Lift forces

Drag forces

$$F_D = \frac{1}{2}\rho V_r^2 c C_D$$

Equation No. 2: Drag forces where, is the air density in kg/m^3, V_r is the relative wind speed at the element (m/s), c is the chord length in m, C_L and C_D are the lift and drag coefficients, respectively.

2.1.2 Power Coefficient

The performance of the wind turbine is quantified by the power coefficient using Equation number 3,

$$C_p = \frac{P}{\frac{1}{2}\rho A V^3}$$

Equation No. 3: Power coefficient

where, P is the power output, A is the swept area of the rotor, and V is the free stream wind speed.

2.1.3 Axial Induction Factor (a)

Axial induction factor represents reduction in the wind speed at the rotor plane, and is given by equation number 4,

$$a = 1 - \frac{V_r}{V}$$

Equation No. 4: Axial induction factor

2.1.4 Tangential Induction Factor (a')

It represents the slowing of air in the tangential direction due to the blade rotation given by equation number 5,

$$a' = \frac{\omega R}{2V}(1 - a)$$

Equation No. 5: Tangential induction factor

3.0 Key Blade Design Parameters

The design parameters of blades dictate the aerodynamic performance and efficiency of MWTs, directly affecting energy capture and power output. The parameters encompass chord length, twist angle, solidity, airfoil selection, and tip-speed ratio, each contributing distinctly to the optimization of turbine performance under diverse wind conditions.

3.1 Chord Length and its Influence

The chord length c refers to the width of the blade cross-section. Increasing the chord length enhances the lift force generated by the blade, which improves power output. However, beyond a certain point, further increases in chord length introduce excessive drag, reducing efficiency.

The ideal chord distribution along the blade span can be expressed as Equation number 6,

$$c(r) = c_o\left(1 - \frac{r}{R}\right)$$

Equation No. 6: Chord distribution along the blade span

where co is the chord length at the root, and R is the rotor radius. An optimal chord length maximizes the power coefficient Cp by balancing lift and drag forces.

3.2 Twist Angle and Angle of Attack

The twist angle (r) of a blade ensures that each section maintains an optimal angle of attack with respect to the incoming wind. This is especially important because the relative wind direction changes along the span of the blade. The twist angle is expressed as equation number 7,

$$\theta(r) = \theta_o - B\left(\frac{r}{R}\right)$$

Equation No. 7: Twist angle

where θ_o is the twist angle at the root, and B is a constant twist rate. A well-optimized twist distribution improves aerodynamic efficiency by ensuring that each section generates maximum lift with minimal drag.

3.3 Solidity and Number of Blades

Solidity σ is defined as the ratio of the total blade area to the swept area of the rotor. It is a key factor in determining the start-up behaviour and performance of the turbine at low wind speeds. It is given by equation number 8,

$$\sigma = \frac{B\,c}{\pi\,R}$$

Equation No. 8: Solidity

Where B is the number of blades. Higher solidity improves starting to torque, allowing the turbine to operate efficiently at low wind speeds. However, increased solidity may reduce efficiency at high wind speeds by increasing drag.

3.4 Airfoil Selection

The choice of airfoil determines the aerodynamic characteristics of the blades, such as the lift-to-drag ratio. Micro-wind turbines typically operate at low Reynolds numbers, which makes them more susceptible to flow separation. Airfoils such as SG6043 and NACA 4415 are commonly used because they offer good performance under these conditions.

The lift coefficient CL and drag coefficient CD are defined as follows and it is calculated by Equation number 9 and 10 respectively.

$$C_L = \frac{F_L}{\frac{1}{2}\rho V_r^2 c}$$

Equation No. 9: Lift coefficient

and

$$C_D = \frac{F_D}{\frac{1}{2}\rho V_r^2 c}$$

Equation No. 10: Drag coefficient

3.5 Tip Speed Ratio (TSR)

The tip speed ratio λ is the ratio of the blade tip speed to the free-stream wind speed and is calculated by Equation number 11,

$$\lambda = \frac{\omega R}{V}$$

Equation No. 11: Tip speed ratio

An optimal TSR ensures that the blades operate at their maximum efficiency. MWTs generally have lower TSRs than large turbines due to mechanical losses and higher drag.

4.0 Analysis and Discussion

4.1 Power Generation vs. Wind Speed

The chord length markedly affects the power output of micro-wind turbines by regulating the aerodynamic interaction between the blade and the wind. Augmenting the chord length amplifies the lift force produced by the blade, thereby enhancing energy capture and increasing power output, particularly at low wind velocities[12]. Excessively large chord lengths can elevate drag, thereby constraining the optimal tip speed ratio and diminishing the power coefficient[13]. Enhancing the chord length distribution along the blade guarantees that each segment effectively contributes to power generation, with optimal performance attained when the non-dimensional chord length is approximately 0.4. This method optimizes the power coefficient Cp by reducing energy losses due to drag and achieving an optimal balance of aerodynamic forces.

4.2 Effect of Twist Angle on Aerodynamic Performance

The twist angle of micro-wind turbine blades profoundly influences their aerodynamic efficiency and energy production. An optimized twist angle guarantees that every segment of the blade attains the ideal angle of attack, thereby maximizing lift and minimizing drag across diverse wind velocities[14]. Research indicates that twisted blades exhibit superior alignment with airflow relative to untwisted blades, enhancing self-starting ability and ensuring consistent torque production[15]. Moreover, blades featuring optimized twist can undergo slight deformation under aerodynamic stress, dynamically adjusting their angle to sustain efficiency across different wind velocities[13]. Moreover, an improper distribution of twist angles can diminish efficiency by causing uneven loading, resulting in power output losses, thereby underscoring the necessity of meticulous aerodynamic design[16].

4.3 Influence of Solidity and Number of Blades

The solidity and number of blades have a direct impact on the aerodynamic performance and power output of micro-wind turbines. Increasing solidity enhances aerodynamic performance by raising torque and enabling the turbine to perform efficiently at low wind speeds[17]. However, higher solidity can also increase drag, potentially reducing efficiency at higher wind speeds[17]. Furthermore, adding more blades generally improves energy capture at low wind speeds, reducing the cut-in wind speed, but excessive blade numbers may introduce aerodynamic interference, lowering overall performance[9]. However, excessive blade numbers can lead to aerodynamic interference, diminishing performance gains beyond an optimal point, usually between 12 and 14 blades for some designs[10]. Optimizing both solidity and blade count ensures maximum power output while maintaining low cut-in wind speeds.

4.4 Selection of Airfoil and Reynolds Number

The choice of airfoil and the Reynolds number substantially affect the power output of micro-wind turbines by altering the aerodynamic efficiency of the blades. Airfoils with low Reynolds numbers are crucial for achieving optimal lift-to-drag ratios, thereby enhancing turbine efficiency in typical low-speed wind conditions found in urban settings[18,19]. MWTs frequently function at low Reynolds numbers, where flow separation is prevalent, diminishing efficiency. The utilization of airfoils such as SG6043 and SD7037, designed for low Reynolds number flows, enhances the lift-to-drag ratio, thereby improving power output in low-wind scenarios[18]. As the Reynolds number increases, the lift coefficient increases, and the blades encounter diminished drag, thereby improving the turbine's power output and efficiency[20]. Consequently,

aligning the airfoil design with the operational Reynolds number is essential for optimizing micro-wind turbine performance.

5.0 Conclusion

This paper emphasizes the significant impact of blade design parameters including chord length, twist angle, solidity, number of blades, airfoil selection, and Reynolds number on the performance of micro-wind turbines. Optimizing these parameters is crucial for balancing lift and drag forces, thereby ensuring efficient energy capture, particularly in low-wind conditions. An augmentation in chord length improves lift but may elevate drag if not optimally allocated. A precisely calibrated twist angle preserves the optimal angle of attack throughout the blade span, enhancing aerodynamic efficiency. Increased solidity and additional blades enhance startup performance but may create drag at elevated speeds. Furthermore, aligning airfoil profiles with the turbine's Reynolds number guarantees minimal flow separation, thereby optimizing lift-to-drag ratios. These insights offer a thorough comprehension of how design decisions affect power output and efficiency. By meticulously calibrating these parameters, micro-wind turbines can enhance performance, rendering them efficient solutions for decentralized energy generation across various environments.

6.0 References

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