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Efficiency Analysis of Backward Sweep Winglet Tip on Offshore Wind Turbine Blades under Low Wind Speed Conditions

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Abstract

This study investigates the effect of backward sweep winglet tip modifications on the aerodynamic efficiency of offshore wind turbine blades operating under low wind speed conditions. The turbine model used in this research is the NREL Phase VI horizontal-axis wind turbine equipped with S809 airfoil profiles. Computational Fluid Dynamics (CFD) simulations were conducted using ANSYS Fluent with the k–ω SST turbulence model. Three backward sweep winglet angles (25°, 50°, and 60°) were evaluated at wind speeds ranging from 5 to 15 m/s. The results show that backward sweep winglets significantly influence torque generation, power output, and power coefficient (Cp), particularly at low wind speeds. The highest Cp value was achieved by the 60° backward sweep winglet at 5 m/s, indicating improved aerodynamic performance through reduced tip vortex intensity and flow leakage. All obtained Cp values remained below the Betz limit, confirming the physical validity of the results. These findings demonstrate that backward sweep winglet tips are effective for enhancing offshore wind turbine performance in regions with low wind speed characteristics, such as Indonesian coastal waters.

Keywords: offshore wind turbine; CFD simulation; blade tip design; rearward sweep; aerodynamic efficiency; NREL Phase VI.

1. Main Section

The increasing demand for renewable and environmentally friendly energy has intensified global interest in wind energy. Offshore wind turbines offer significant advantages due to higher and more stable wind speeds compared to onshore locations. However, many coastal regions, including Indonesia, are dominated by relatively low wind speed conditions, which limit turbine efficiency. Therefore, aerodynamic optimization of wind turbine blades is crucial to maximize energy extraction under such conditions.

One of the major aerodynamic losses in wind turbines occurs at the blade tip due to the formation of tip vortices. These vortices increase induced drag and reduce overall efficiency. Tip blade modifications, such as winglets and sweep configurations, have been proposed to mitigate these losses. Previous studies indicate that backward sweep winglets can reduce vortex strength and improve aerodynamic performance. However, their effectiveness under low wind speed offshore conditions remains limitedly explored. This study aims to analyze the influence of backward sweep winglet angles on turbine efficiency using CFD simulations.

2. Literatur Review

Wind energy is a clean and renewable energy source with significant potential for offshore applications due to higher and more stable wind conditions compared to onshore environments. However, many coastal regions, including Indonesia, are dominated by low wind speed conditions, generally below 10 m/s. Since wind power output is proportional to the cube of wind speed, turbines operating in such environments require aerodynamic optimization to maintain efficiency.

The performance of wind turbines is governed by aerodynamic forces acting on the blades, primarily lift and drag. Lift generates rotor torque and power, while drag contributes to energy losses. Excessive angles of attack can lead to

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flow separation and stall, reducing aerodynamic efficiency. Torque and thrust are key mechanical responses resulting from these aerodynamic interactions, directly influencing power generation and structural loading.

Horizontal Axis Wind Turbines (HAWTs) are widely used due to their superior efficiency and adaptability to offshore conditions. The NREL Phase VI turbine is commonly adopted as a benchmark model in aerodynamic studies because of its well-documented experimental data and its use of the S809 airfoil, which is optimized for low to moderate wind speeds and exhibits stable aerodynamic behavior.

A major source of aerodynamic loss in wind turbines occurs at the blade tip due to the formation of tip vortices. Tip blade modifications, such as winglets, are designed to reduce induced drag by controlling spanwise flow. Downwind winglets combined with backward sweep configurations can further weaken tip vortices, improve flow stability, and enhance energy extraction, particularly under low wind speed conditions.

Wind turbine efficiency is commonly evaluated using the power coefficient (Cp), which represents the ratio of extracted power to available wind energy. The theoretical maximum efficiency is limited by the Betz limit at 59.3%. Therefore, blade design optimization, including backward sweep winglet tips, aims to increase Cp while remaining within theoretical and physical constraints.

3. Methodology

This research was conducted using a numerical approach based on Computational Fluid Dynamics (CFD) to investigate the aerodynamic performance of offshore wind turbine blades with backward sweep winglet tip modifications under low wind speed conditions. The methodology was designed to systematically evaluate the influence of different sweep angles on torque, power output, and power coefficient.

3.1 Wind Turbine Model

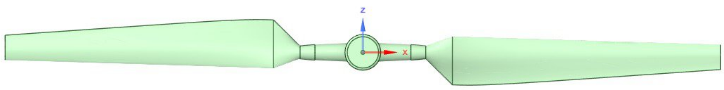
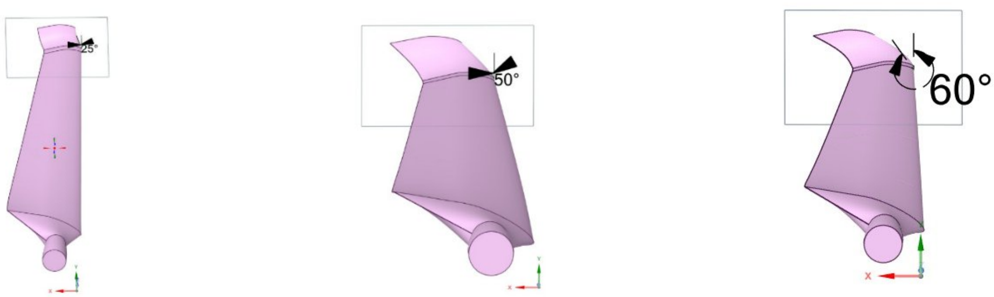


Figure 1 NREL Phase VI Blade

The reference turbine model used in this study was the NREL Phase VI horizontal axis wind turbine. This turbine is widely recognized as a benchmark model due to the availability of comprehensive experimental data from wind tunnel tests. The turbine consists of two blades with a rotor diameter of 10.058 m and employs the S809 airfoil, which is specifically designed for low to moderate wind speed applications. The airfoil exhibits favorable lift-to-drag characteristics and stable stall behavior, making it suitable for offshore environments with limited wind resources.

3.2 Tip Blade Geometry and Variations

***Blade* 1**	***Blade* 2**	***Blade* 3**



25°	50°	60°

Figure 2 Variations

Backward sweep winglet modifications were applied at the blade tip to reduce aerodynamic losses caused by tip vortex formation. Three sweep angle variations were investigated: 25°, 50°, and 60°. These configurations were selected to represent small, medium, and large backward sweep geometries. The winglets were oriented in the downwind direction to improve flow control near the blade tip and enhance aerodynamic efficiency, particularly at low wind speeds.

3.3 Computational Domain and Boundary Conditions

The computational domain was divided into two main regions: a rotating inner domain containing the turbine rotor and a stationary outer domain representing the surrounding airflow. This domain configuration allows accurate modeling of the interaction between the rotating blades and incoming wind. The inlet boundary condition was defined as a velocity inlet with wind speeds of 5, 7, 10, 13, and 15 m/s, representing low to moderate wind conditions. A pressure outlet boundary condition was applied at the outlet, while symmetry conditions were imposed on the side walls to minimize boundary interference effects. Blade surfaces were modeled as no-slip walls to accurately capture viscous effects.

3.4 Numerical Setup

The simulations were performed using ANSYS Fluent under steady-state conditions. Airflow was assumed to be incompressible due to the relatively low wind speeds involved. The k–ω Shear Stress Transport (SST) turbulence model was employed because of its robustness in predicting near-wall flows and flow separation, which are critical in wind turbine aerodynamics. Rotor rotation was modeled using the Multiple Reference Frame (MRF) approach, enabling steady-state representation of rotational effects with reasonable computational efficiency.

3.5 Mesh Generation and Validation

A structured–unstructured hybrid mesh was generated for the computational domain, with mesh refinement applied near the blade surfaces and tip region to accurately capture flow gradients and vortex structures. A mesh convergence study was conducted using several mesh densities to ensure numerical accuracy. Based on the convergence of torque values and computational efficiency, a mesh containing approximately one million cells was selected as the optimal configuration.

Model validation was carried out by comparing CFD results with available experimental and numerical data from previous NREL Phase VI studies. The comparison showed acceptable error levels, confirming that the numerical setup and mesh resolution were adequate for performance evaluation.

3.6 Performance Evaluation Parameters

The aerodynamic performance of each blade configuration was evaluated using torque, power output, and power coefficient (Cp). Torque values obtained from the simulations were used to calculate mechanical power based on the rotor angular velocity. The power coefficient was then calculated as the ratio between the extracted power and the available kinetic energy of the wind. This parameter was used as the primary indicator of turbine efficiency and served as the basis for comparing different backward sweep winglet designs.

4. Results and Discussion

Table 1 Power Calculation

Models	**Velocity (m/s)**	**Torque**	**Power (W)**	***Cp***
	5	295	2224	0,366
25 *Deg*	7	396	2988	0,179
	10	615	4636	0,095

	13	928	6997	0,065
	15	1089	8211	0,050
50 *Deg*	5	300	2262	0,372
	7	403	3039	0,182
	10	625	4716	0,097
	13	900	6786	0,064
	15	1110	8369	0,051
60 *Deg*	5	305	2300	0,378
	7	407	3069	0,184
	10	765	5768	0,119
	13	908	6846	0,064
	15	1114	8400	0,051

The CFD simulation results show that turbine torque increases with wind speed for all backward sweep winglet configurations due to the increase in available kinetic energy. Among the tested designs, the 25° backward sweep winglet generally produces higher torque values, indicating effective aerodynamic loading along the blade span.

The power coefficient (Cp) analysis reveals that turbine efficiency is highest at low wind speeds, particularly at 5 m/s for all configurations. As wind speed increases, Cp decreases despite rising power output, mainly due to stronger wake formation, increased induced drag, and flow separation near the blade tip. This behavior confirms that the turbine is optimized for low wind speed operation.

Flow visualization indicates that backward sweep winglets reduce tip vortex intensity and flow leakage at low wind speeds, resulting in a more stable wake. At higher wind speeds, wake length and vortex strength increase for all configurations, although winglets continue to provide partial flow control.

Among the evaluated designs, the 60° backward sweep winglet achieves the highest Cp at low wind speeds, demonstrating superior efficiency in reducing aerodynamic losses. All Cp values remain below the Betz limit, confirming the physical validity of the results. Therefore, the 60° backward sweep winglet is identified as the most optimal configuration for offshore wind turbines operating in low wind speed conditions.

5. Kesimpulan

This study investigated the aerodynamic performance of an offshore horizontal axis wind turbine equipped with backward sweep winglet tip modifications under low wind speed conditions using a Computational Fluid Dynamics (CFD) approach. The numerical results clearly indicate that blade tip geometry plays a critical role in improving turbine efficiency, particularly in regions characterized by low and moderate wind speeds such as Indonesian offshore waters. The simulation results show that turbine torque and mechanical power increase with increasing wind speed due to the higher kinetic energy available in the incoming airflow; however, the power coefficient (Cp), which represents aerodynamic efficiency, decreases at higher wind speeds as a result of increased aerodynamic losses, including stronger wake development, enhanced induced drag, and flow separation near the blade tip and along the blade surface. All backward sweep winglet configurations achieved their maximum Cp values at a wind speed of 5 m/s, confirming that the proposed blade designs are most effective in low wind speed operating conditions. Among the investigated configurations, the 60° backward sweep winglet demonstrated the best overall aerodynamic performance by consistently achieving the highest Cp values at low wind speeds, which can be attributed to its superior capability in suppressing tip vortex formation, reducing spanwise flow leakage, and improving flow stability in the blade tip region. Furthermore, all Cp values obtained in this study remained below the theoretical Betz limit of 0.593, indicating that the simulation results are physically realistic and consistent with fundamental wind turbine aerodynamic theory. Based on these findings, the 60° backward sweep winglet is recommended as the most optimal tip blade configuration for offshore wind turbine applications in low wind speed regions. For future research, it is recommended to investigate a wider range of sweep angles and alternative tip geometries, such as forward sweep or hybrid winglet designs, as well as to incorporate structural, fatigue, and aeroelastic analyses to evaluate long-term durability. Additionally, experimental validation through wind tunnel testing or field measurements is strongly suggested to further confirm the reliability of the numerical results and support practical implementation.

6. Equation

6.1 Wind Power Equation

The total kinetic power available in the wind passing through the rotor swept area is given by:

$$P_{wind} = \frac{1}{2}\rho A V^3 \tag{1}$$

6.2 Power Coefficient (Cp)

The power coefficient represents the aerodynamic efficiency of the wind turbine and is defined as:

$$C_p = \frac{P_{turbine}}{P_{wind}} = \frac{T \cdot \omega}{\frac{1}{2}\rho A V^3} \tag{2}$$

Nomenclature

ω	Angular velocity of the rotor (rad/s)
R	Rotor radius or blade length (m)
V	Free-stream wind velocity (m/s)
T	Aerodynamic torque (N·m)
P	Mechanical power of the turbine (W)
ρ	Air density (kg/m³)
A	Rotor swept area (m²)
Cp	Power coefficient (–)

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