

Small-Scale Wind Energy Conversion System at Low Wind Speeds Using QBlade

Triwahju Hardianto^{1*}, Widjonarko Widjonarko², Bambang Sujanarko³, Devita Ayu Larasati⁴

^{1,2,3,4} Department of Electrical Engineering, Faculty of Engineering, University of Jember, Jember, Indonesia

Article Info

Article history:

Received October 20, 2026

Revised October 27, 2026

Accepted October 30, 2026

Keywords:

Small-scale wind turbine

Airfoil NACA 4412

Qblade 2.8.0.6

Blade Element Momentum

Turbine BEM

ABSTRACT

This study aims to assess the aerodynamic performance and predicted power output of a 500 W small-scale wind energy conversion system under low-to-moderate wind speeds using QBlade version 2.0.8.6. A three-bladed horizontal-axis wind turbine with a 4 m rotor diameter was designed using the NACA 4412 airfoil for a design wind speed of 6 m/s and a tip-speed ratio (TSR) of approximately 6. Rotor and turbine performance were evaluated using Blade Element Momentum (BEM) simulations, considering Stall Control, Pitch Control, and Prescribed operating strategies. The rotor achieved a maximum power coefficient C_p of approximately 0.41 at a TSR of 5–6. Among the three strategies, Pitch Control maintained the nominal 500 W output at wind speeds above approximately 7 m/s. In contrast, Stall Control and Prescribed produced predicted outputs of 2317.35 W and 1980.30 W, respectively, at 15 m/s, exceeding the nominal power rating. A fixed pitch angle of 5°, a loss factor of 0.1, and fixed losses of 25 W were incorporated as modelling assumptions for the preliminary prediction of net output electrical power generation. These findings demonstrate that the selected power regulation strategy substantially influences the predicted power characteristics of a small-scale wind turbine. Pitch Control provides the most consistent output with the 500 W rating among the strategies investigated, while the other strategies require further assessment of power limitation under higher wind speeds. The results provide a numerical basis for evaluating small wind turbine performance in low-wind-speed applications.

This is an open access article under the [CC BY-SA](https://creativecommons.org/licenses/by-sa/4.0/) license.



Triwahju Hardianto,

Department of Electrical Engineering, Faculty of Engineering, University of Jember, Jember 68121, Indonesia

Email: triwahju.teknik@unej.ac.id ; Orcid ID : <https://orcid.org/0009-0008-2760-4353>

1. INTRODUCTION

The increasing demand for clean, decentralized, and sustainable electricity has encouraged the development of small-scale wind energy conversion systems (WECS), particularly for applications in areas with limited grid access and relatively low wind speeds. However, extracting useful energy from low-speed wind remains challenging because the available wind power is strongly dependent on wind speed, while turbine performance is also influenced by blade geometry, airfoil characteristics, and operating conditions. Umar et al. [1] investigated the design and optimization of a small-scale horizontal-axis wind turbine (HAWT) blade for energy harvesting in low-wind-profile areas. Zarketa-Astigarraga et al. [2] examined the effects of turbulence and blade surface degradation on the annual energy production of small-scale wind turbines, while Terefa et al. [3] investigated the optimal design of mixed-airfoil blades for small-scale HAWTs. These studies highlight

the importance of aerodynamic design and operating conditions in improving the performance of small wind turbines. Nevertheless, selecting an appropriate blade configuration alone does not fully explain how a turbine performs across a range of wind speeds or how its power output can be regulated according to a specified power rating.

Blade Element Momentum (BEM) theory is widely used in preliminary wind turbine design because it combines the aerodynamic characteristics of individual blade sections with momentum principles applied to the rotor. Radi and Djebli [4] demonstrated the application of BEM theory for the optimal design of a horizontal-axis wind turbine. Assessing turbine performance under realistic wind conditions is also important. Abad et al. [5] evaluated small wind turbine performance under variable urban wind conditions, emphasizing the relevance of wind variability in performance assessment. For low-wind-speed applications, Kumar et al. [6] investigated the design and analysis of a small wind turbine using QBlade, while Zidane and Mahmood [7] conducted aerodynamic design and analysis of a small horizontal-axis wind turbine using the same software. Früh [8] examined the assessment of small wind energy systems using regional weather data, and Younoussi and Ettaouil [9] numerically studied the aerodynamics of a small HAWT operating at low wind speed. Collectively, these studies provide a basis for applying aerodynamic analysis and numerical simulation to small-scale wind energy systems. However, further analysis is needed to connect rotor aerodynamic performance with turbine-level power regulation for a turbine designed around a specific nominal power rating.

The performance of small wind turbines is affected not only by blade aerodynamics but also by rotor configuration, operating conditions, and the strategy used to regulate power. Rosato et al. [10] reviewed the geometry, materials, costs, and performance of commercial small-scale horizontal- and vertical-axis wind turbines. Strojny [11] investigated the efficiency of a small-scale wind turbine with a rotor adapted for low wind speeds, while Kulak et al. [12] experimentally examined the influence of rotor solidity and blade pitch on small HAWT performance. Kadhimi et al. [13] studied low-speed wind energy harvesting using a micro-wind-turbine system, and Mthethwa et al. [14] described the development of a portable small wind turbine for integration into mobile cooling technology. In addition, Signoretti et al. [15] compared the aerodynamic efficiency of small-diameter wind turbine blades using NACA 4412 and Clark Y airfoils. Hasan et al. [16] experimentally examined electrical power generation from a commercial small-scale wind turbine with a modified aerodynamic design. Although these studies address several important aspects of small wind turbine performance, a systematic comparison of different turbine power-regulation strategies for a 500 W-class HAWT over a common wind-speed range remains a relevant subject for further investigation.

The generator is another important component of a WECS because the mechanical power delivered by the turbine must be converted into electrical power. Permanent magnet synchronous generators (PMSGs) are potential options for small-scale wind energy applications, including systems designed for relatively low rotational speeds. Aika et al. [17] evaluated the performance of a mini PMSG for a wind energy system, while Smaza et al. [18] investigated the selection of a suitable permanent magnet synchronous machine design for a small wind turbine. These studies demonstrate the relevance of generator selection and characterization in small-scale wind energy conversion. However, the present study does not incorporate an integrated PMSG and power-converter model in QBlade. Therefore, its primary focus is the aerodynamic and turbine-level performance predicted by QBlade rather than the experimentally verified electrical output of a generator. The assumed generator rating of 500 W is used as a reference for evaluating the predicted turbine power, not as evidence that the generator delivers 500 W of actual electrical power.

To address this research gap, the present study investigates a three-bladed HAWT with a rotor diameter of 4 m and NACA 4412 airfoils, designed around a nominal generator capacity of 500 W. The blade design is developed using a design tip-speed ratio of approximately 6 and a specified design angle of attack. The aerodynamic characteristics of the rotor are first evaluated using Rotor BEM in QBlade version 2.0.8.6. Subsequently, Turbine BEM simulations are conducted over wind speeds ranging from 3 to 15 m/s to assess the predicted turbine power under three operating strategies: Stall Control, Pitch Control, and Prescribed. For the preliminary power assessment, a fixed pitch angle of 5°, a loss factor of 0.1, and fixed losses of 25 W are included as modeling assumptions. These parameters are used to examine the influence of the selected operating strategy and assumed losses on the predicted power; they do not represent measured generator or converter losses.

The main objective of this study is to evaluate how the three power-regulation strategies influence the predicted power output of a 500 W-class small-scale HAWT under low-to-moderate wind-speed conditions. Specifically, the analysis examines the relationship between wind speed and predicted turbine power, identifies the wind-speed range in which the predicted power approaches or exceeds the 500 W reference rating, and compares the power characteristics obtained using Stall Control, Pitch Control, and Prescribed strategies. The study also evaluates the rotor power coefficient in relation to the tip-speed ratio to connect the aerodynamic performance of the blade with the subsequent turbine-level analysis. The contribution of this work is therefore a consistent comparison of rotor aerodynamic performance and predicted turbine power regulation within a

single QBlade-based workflow. The results are intended to identify differences among the three operating strategies and provide a numerical basis for further experimental validation using an actual generator and electrical conversion system.

2. METHOD

The aerodynamic performance of the horizontal-axis wind turbine (HAWT) was evaluated using the Blade Element Momentum (BEM) method implemented in QBlade. The BEM method combines blade-element aerodynamic forces with momentum theory to estimate the rotor performance under different wind conditions. The approach has been applied in recent studies involving small-scale wind turbine design, aerodynamic optimization, and validation of QBlade simulation results [19], [20].

The axial induction factor (a) represents the fractional reduction in wind velocity as the airflow passes through the rotor disc. It is defined as the relative difference between the free-stream wind velocity (V_∞) and the axial velocity at the rotor plane (V_{rotor}), as expressed in (1).

$$a = 1 - \frac{V_{\text{rotor}}}{V_\infty} \quad (1)$$

where (V_∞) is the free-stream wind velocity (m/s) and (V_{rotor}) is the axial wind velocity at the rotor plane (m/s). The induction factor describes the influence of the rotor on the approaching airflow and is used in the momentum-based evaluation of rotor performance [19].

The angle of attack (α) is the angle between the relative wind velocity vector and the local airfoil chord line. It is determined by the relative inflow angle (ϕ), the local blade twist angle (θ_{twist}), and the blade pitch angle (θ_{pitch}), as given in (2).

$$\alpha = \phi - (\theta_{\text{twist}} + \theta_{\text{pitch}}) \quad (2)$$

where ϕ is the relative inflow angle, (θ_{twist}) is the local geometric twist angle, and (θ_{pitch}) is the blade pitch angle. The angle of attack affects the lift and drag forces generated by the NACA 4412 airfoil and consequently influences the aerodynamic torque and power coefficient of the rotor. The blade geometry and operating conditions are therefore important parameters in the aerodynamic optimization of small wind turbines [19], [20].

The mechanical power extracted by the rotor from the kinetic energy of the incoming wind is expressed in terms of the air density, rotor swept area, free-stream wind velocity, and power coefficient, as expressed in (3).

$$P = \frac{1}{2} \rho A V_\infty^3 C_p \quad (3)$$

where P is the mechanical power extracted by the rotor (W), ρ is the air density (kg/m^3), A is the rotor swept area (m^2), V_∞ is the free-stream wind velocity (m/s), and C_p is the dimensionless power coefficient. For a rotor with radius R , the swept area is calculated as $A = \pi R^2$. An air density of 1.225 kg/m^3 may be assumed under standard reference conditions, provided that this assumption is consistent with the simulation settings.

The power coefficient represents the ratio of the mechanical power extracted by the rotor to the kinetic power available in the incoming wind. It is calculated as expressed in (4).

$$C_p = \frac{P}{\frac{1}{2} \rho A V_\infty^3} \quad (4)$$

The coefficient C_p depends on the tip-speed ratio, blade pitch angle, airfoil characteristics, and rotor geometry. Therefore, the power coefficient obtained from QBlade can be used to evaluate the aerodynamic performance of the three-bladed wind turbine under different wind speeds and operating conditions. Recent studies have employed this parameter to compare turbine designs and assess the effectiveness of blade optimization [19], [20].

The axial thrust force represents the aerodynamic force exerted by the wind on the rotor in the wind direction. It is calculated using the thrust coefficient, air density, rotor swept area, and free-stream wind velocity, as given in (5).

$$T = \frac{1}{2} \rho A V_{\infty}^2 C_t \quad (5)$$

Where T is the axial thrust force (N) and C_t is the dimensionless thrust coefficient. Under the ideal actuator-disc momentum theory, the thrust coefficient is related to the axial induction factor as expressed in (6).

$$C_t = \frac{T}{\frac{1}{2} \rho A V_{\infty}^2} = 4a(1-a) \quad (6)$$

Equation (6) applies under the conventional ideal momentum-theory assumptions and should not be treated as universally valid at high axial induction factors or under complex wake conditions. The thrust coefficient is useful for evaluating the aerodynamic loading of the rotor and understanding how changes in wind speed and rotor operating conditions influence the structural loads. Related aerodynamic loading analyses have been performed using QBlade and compared with computational fluid dynamics (CFD) simulations [21].

The aerodynamic torque is generated by the tangential component of the aerodynamic forces acting on the rotor blades. It can be calculated from the mechanical power and angular rotational speed of the rotor, as expressed in (7).

$$Q = \frac{P}{\Omega} \quad (7)$$

where Q is the aerodynamic torque (N·m), P is the rotor mechanical power (W), and Ω is the angular rotational speed (rad/s). If the rotor speed is specified in revolutions per minute (rpm), the angular rotational speed is calculated as in (8)

$$\Omega = \frac{2\pi \cdot N}{60} \quad (8)$$

where (N) is the rotor rotational speed in rpm.

The blade pitch angle θ_{pitch} changes the orientation of the blade relative to the rotor plane and affects the angle of attack. Pitch adjustment can therefore be used to regulate aerodynamic power, particularly when the turbine operates near or above its rated wind speed. In this study, the pitch angle is considered in evaluating the turbine's aerodynamic response under different operating conditions. Recent research has examined the effects of blade pitch and rotor geometry on the performance of small horizontal-axis wind turbines [20], [21].

The numerical investigation was conducted to design and evaluate a three-bladed horizontal-axis wind turbine (HAWT) with a nominal generator capacity of 500 W. The simulation procedure began with the generation and aerodynamic analysis of the NACA 4412 airfoil to obtain the lift and drag polar data required for blade design. The airfoil data were then used to develop a rotor with a diameter of approximately 4 m, based on a design wind speed of 6 m/s and a design tip-speed ratio (TSR) of approximately 6. The blade geometry was defined using radial stations with appropriate chord and twist distributions determined from the local flow angle and design angle of attack. The resulting rotor was evaluated using Rotor Blade Element Momentum (BEM) analysis to determine the power coefficient, thrust coefficient, angle of attack, and axial induction factor. Multi BEM analysis was subsequently performed to investigate rotor performance over different wind speeds and operating conditions. Finally, Turbine BEM simulations were conducted over a wind-speed range of 3–15 m/s using Stall Control, Pitch Control, and Prescribed strategies. A fixed pitch angle of 5°, loss factor of 0.1, and fixed losses of 25 W were incorporated as assumed system losses used to obtain a preliminary prediction of net output electrical power generation.

3. RESULTS AND DISCUSSION

This section presents and discusses the results of the numerical investigation performed using QBlade version 2.0.8.6 for the proposed 500 W small-scale horizontal-axis wind turbine. The results are analyzed to evaluate the aerodynamic performance of the designed rotor and the predicted net output electrical power generation under different operating conditions. The discussion focuses on the aerodynamic characteristics of the NACA 4412 blade, rotor performance obtained from BEM analysis, and turbine performance over the

investigated wind-speed range. The effects of different turbine operating and power-regulation strategies are also discussed to provide an overall assessment of the proposed small-scale wind energy conversion system.



Figure 1. The NACA 4412 Airfoil

Figure 1 shows the NACA 4412 airfoil, which is used as the aerodynamic profile for wind turbine blades. The nomenclature of this 4-digit NACA series describes its primary geometric characteristics: the first digit (4) indicates a maximum camber of 4% of the chord length; the second digit (4) denotes the position of the peak camber at 40% from the leading edge; and the final two digits (12) represent a maximum thickness of 12%. According to the parameter table, this airfoil is defined by 281 coordinate points, with the maximum thickness occurring at the 28.6% position. This geometric configuration provides a high lift-to-drag ratio and stable stall characteristics.

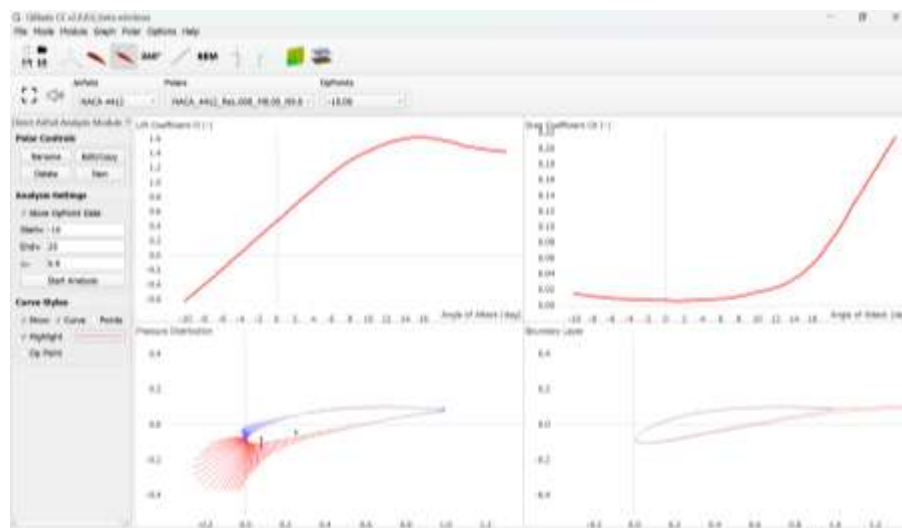


Figure 2. Performance of Lift Coefficient, Drag Coefficient, Pressure Distribution and Boundary Layer

Figure 2 shows the performance of the lift coefficient, drag coefficient, pressure distribution, and boundary-layer characteristics obtained from the QBlade airfoil analysis. The lift coefficient C_l increases almost linearly with the angle of attack from -10° and reaches a maximum value of approximately 1.6 at an angle of attack of around 15° . Beyond this condition, the increase in lift becomes limited, indicating the approach to aerodynamic stall, followed by a slight reduction in C_l . The drag coefficient C_d remains relatively low over the moderate angle-of-attack range, with its minimum value occurring at approximately $2-4^\circ$, before increasing significantly at higher angles of attack. This behavior indicates that the NACA 4412 airfoil provides

a favorable lift-to-drag performance within the moderate operating range. The pressure distribution shows a pressure difference between the upper and lower surfaces of the airfoil, which generates the aerodynamic lift. Meanwhile, the boundary-layer distribution illustrates the development of the flow along the airfoil surface and provides an indication of the aerodynamic flow behavior. Overall, the results confirm that the NACA 4412 airfoil has suitable aerodynamic characteristics for application in the proposed small-scale wind turbine, particularly when operated within an appropriate angle-of-attack range.



Figure 3. Polar Extrapolation to 360

Polar Extrapolation to 360 is shown in Figure 3. Standard 2D aerodynamic analysis typically provides coefficient data only for a limited range of angles of attack (AoA) for instance, from -10° to $+25^\circ$, as shown by the red curve. However, in actual wind turbine BEM (Blade Element Momentum) simulations particularly during high-wind conditions, start-up, parked states, or deep-stall scenarios blade elements may encounter extreme angles of attack, reaching up to $\pm 180^\circ$. Extrapolation methods (such as those developed by Montgomerie or Viterna) are employed to extend aerodynamic coefficient curves to cover the full 360° range of angles of attack (from -180° to $+180^\circ$).

This 360° extrapolation is a critical step prior to running a wind turbine BEM simulation, as it prevents numerical errors (computational failures) that could otherwise occur when blades encounter extreme airflow angles.

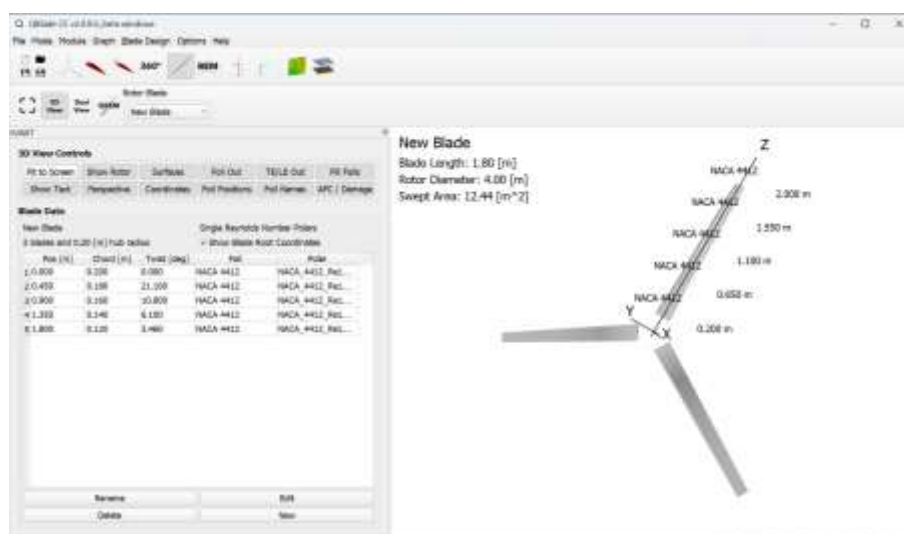


Figure 4. HAWT Blade Design

Figure 4 presents the 3D geometrical design and structural parameters of the Horizontal Axis Wind Turbine (HAWT) blade configured in QBlade. The rotor assembly consists of a 3-bladed configuration with a single blade length of 1.80 m and a hub radius of 0.20 m, yielding a total rotor radius of 2.00 m, a rotor

diameter of 4.00 m, and a total swept area of 12.566 m². The entire blade span utilizes the NACA 4412 aerodynamic airfoil profile evaluated under single Reynolds number polar datasets.

The structural blade geometry is defined across five key radial stations (*Pos*) along the span from root to tip. Station 1 ($0.000 + 0.2 = 0.2$ m) represents the root section with a chord length of 0.200 m and a twist angle of 0.000°. Station 2 ($0.450 + 0.2 = 0.65$ m) features a chord length of 0.180 m with a peak twist angle of 21.100° to accommodate high relative inflow angles near the hub. Station 3 ($0.900 + 0.2 = 1.1$ m) is positioned at mid-span with a chord length of 0.160 m and a twist angle of 10.800°. Station 4 ($1.350 + 0.2 = 1.55$ m) tapers down to a chord of 0.140 m with a twist angle of 6.100°. Finally, Station 5 ($1.800 + 0.2 = 2$ m) at the blade tip reaches a minimum chord of 0.120 m and a twist angle of 3.460°. This progressive tapering in chord length and reduction in twist angle forms an optimized aerodynamic profile that maximizes lift generation while minimizing tip losses.

Overall, the blade's geometric design employs a combination of tapering and aerodynamic twist to maximize wind power extraction and maintain flow stability across the rotor radius.

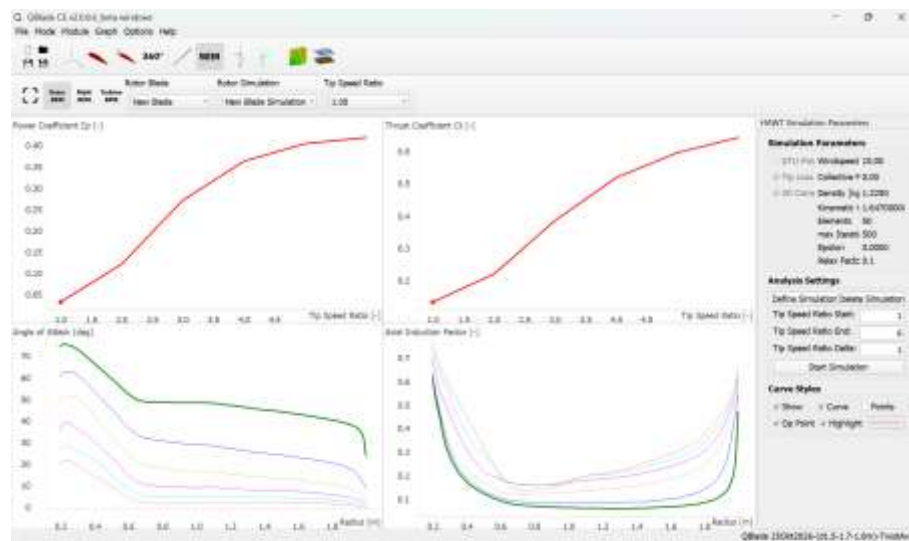


Figure 5. Rotor BEM Simulation

Figure 5 illustrates the Rotor BEM simulation results in QBlade, evaluating the rotor's aerodynamic performance across Tip Speed Ratios (TSR, λ) from 1 to 6 at a wind speed of 10.00 m/s.

The upper-left plot presents the Power Coefficient (C_p), which rises steadily from 0.03 at TSR 1.0 to a peak efficiency of approximately 0.41 at TSR 5.0–6.0, showing optimal kinetic energy extraction at higher rotational speeds. The upper-right graph depicts the Thrust Coefficient (C_t), showing a continuous increase from 0.13 to over 0.63 across the TSR range, reflecting greater axial aerodynamic loads on the rotor assembly as rotation accelerates.

The lower-left chart shows the Angle of Attack (α) distribution along the blade radius (0.2 m to 1.8 m). At low TSRs, high angles ($> 70^\circ$) near the root cause severe stalling, but these decrease to optimal operational angles (0° – 15°) as TSR increases. Finally, the lower-right plot highlights the Axial Induction Factor (a), displaying sharp spikes near the root ($r \approx 0.2$ m) and tip ($r \approx 1.8$ m) due to hub and tip losses, while remaining stable between 0.05 and 0.20 along the main span.

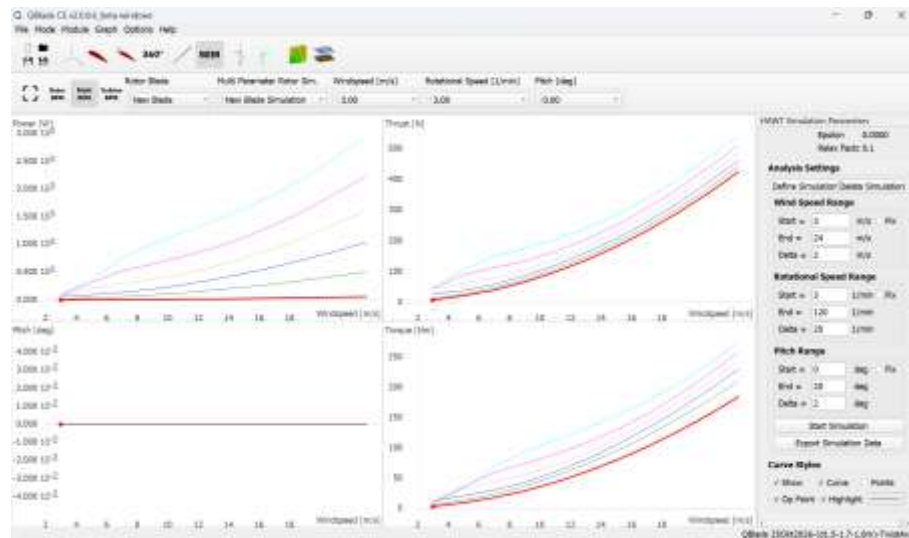


Figure 6. Multi Parameter BEM Simulation

Figure 6 illustrates the Multi-Parameter Rotor Simulation (Multi BEM) results in QBlade, assessing rotor performance across wind speeds from 3 m/s to 24 m/s and rotational speeds from 3 rpm to 120 rpm under a fixed pitch angle of 0.00° .

The upper-left plot demonstrates mechanical power (P), which increases exponentially with wind speed following the cubic energy relation ($P \propto V_\infty^3$). At the maximum speed of 120 rpm and 24 m/s wind speed, the rotor reaches a peak power output of approximately 3.0×10^3 W (3 kW). The upper-right graph shows the axial thrust force (T), which grows quadratically from near 0 N to over 500 N at 24 m/s as higher rotational speeds increase aerodynamic drag on the rotor disc.

The lower-left chart reflects a constant pitch angle of 0.00° , confirming an un-pitched baseline simulation. Lastly, the lower-right chart highlights shaft torque (Q), which rises consistently with wind speed and rotational speed to a maximum of about 270 Nm at 24 m/s. This demonstrates strong tangential force generation for driving the generator shaft across varying operational conditions.

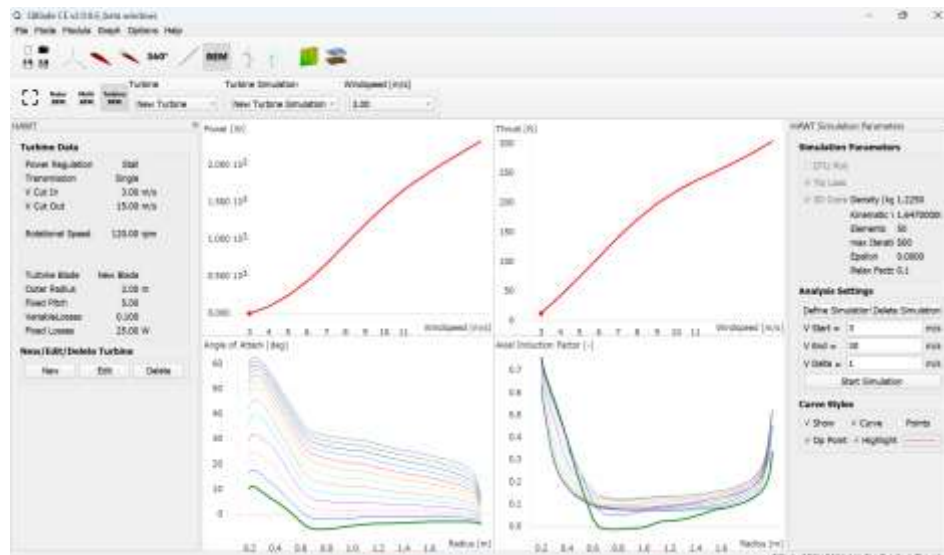


Figure 7. Turbine BEM Simulation with Stall Control Power Regulation

Figure 7 illustrates the aerodynamic performance results from the Turbine BEM Simulation module in QBlade under passive Stall power regulation. The simulation evaluates a Horizontal Axis Wind Turbine (HAWT) operating at a fixed rotational speed of 120.00 rpm with a cut-in wind speed ($V_{\text{cut-in}}$) of 3.00 m/s and a cut-out wind speed ($V_{\text{cut-out}}$) of 15.00 m/s. Additional rotor setup parameters include a fixed pitch angle of 5.00° , an outer rotor radius of 2.00 m, variable losses factor of 0.100, and fixed mechanical/electrical losses of 25.00 W.

The upper-left plot presents the mechanical power output (P) in Watts across wind speeds from 3 m/s to 12 m/s. Power increases smoothly following a cubic trajectory, starting near 0 W at cut-in and rising to approximately 2.3×10^3 W (2.3 kW) at 12 m/s. The upper-right graph displays the axial thrust force (T), which climbs steadily from near 0 N at 3 m/s to over 300 N at 12 m/s due to increased dynamic pressure acting on the fixed-geometry rotor disc.

The lower-left chart depicts the spanwise Angle of Attack (α) distribution along the blade radius (0.2 m to 1.8 m) for various wind speeds. At lower wind speeds, the angle of attack remains moderate across the primary blade span (10° – 20°), but as wind speed increases, α rises sharply near the root ($r \approx 0.2$ m), exceeding 60° . This steep increase triggers passive aerodynamic stall, naturally limiting power absorption without active pitch mechanisms. Lastly, the lower-right chart highlights the Axial Induction Factor (a) across the blade span, showing characteristic high values near the root ($r \approx 0.2$ m) and tip ($r \approx 1.8$ m) caused by hub and tip vortex losses, while maintaining a stable range (0.05 to 0.15) along the mid-span power-producing section.

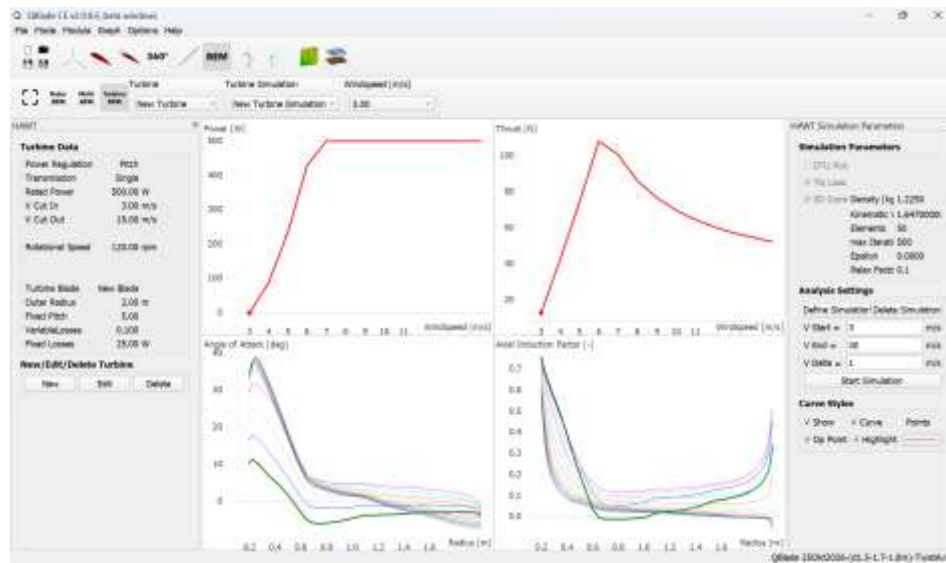


Figure 8. Turbine BEM Simulation with Pitch Control Power Regulation

Figure 8 presents the aerodynamic performance results from the Turbine BEM Simulation module in QBlade under active Pitch Control power regulation. The simulated Horizontal Axis Wind Turbine (HAWT) operates at a constant rotational speed of 120.00 rpm with a cut-in speed ($V_{\text{cut-in}}$) of 3.00 m/s, a cut-out speed ($V_{\text{cut-out}}$) of 15.00 m/s, and a target rated power of 500.00 W. Additional turbine parameters include an outer rotor radius of 2.00 m, a baseline fixed pitch of 5.00° , variable losses factor of 0.100, and fixed losses of 25.00 W.

The upper-left plot demonstrates effective active power regulation. As wind speed increases from 3 m/s, power output rises steeply until reaching the rated threshold of 500 W at approximately 7 m/s. Beyond this rated wind speed, the dynamic pitching mechanism adjusts the blade angle, successfully capping the mechanical power output at a constant 500 W across higher wind speeds up to 12 m/s. The upper-right graph depicts the axial thrust force (T), which reaches a peak near 110 N at the rated wind speed (~ 6 – 7 m/s). Once pitch regulation engages above rated speed, thrust steadily declines to around 50 N at 12 m/s, reducing structural loads during high wind conditions.

The lower-left plot shows the Angle of Attack (α) distribution across the blade radius (0.2 m to 1.8 m). While α spikes up to 38° near the hub ($r \approx 0.2$ m), active pitching regulates α along the primary power-generating span (0.6 m to 1.8 m) within a narrow range of -5° to 5° , preventing severe aerodynamic stall. Lastly, the lower-right plot highlights the Axial Induction Factor (a), showing sharp peaks near the root ($r \approx 0.2$ m) and tip ($r \approx 1.8$ m) due to boundary vortex losses, while maintaining low values (0.00 to 0.15) along the mid-span section under active pitch control.

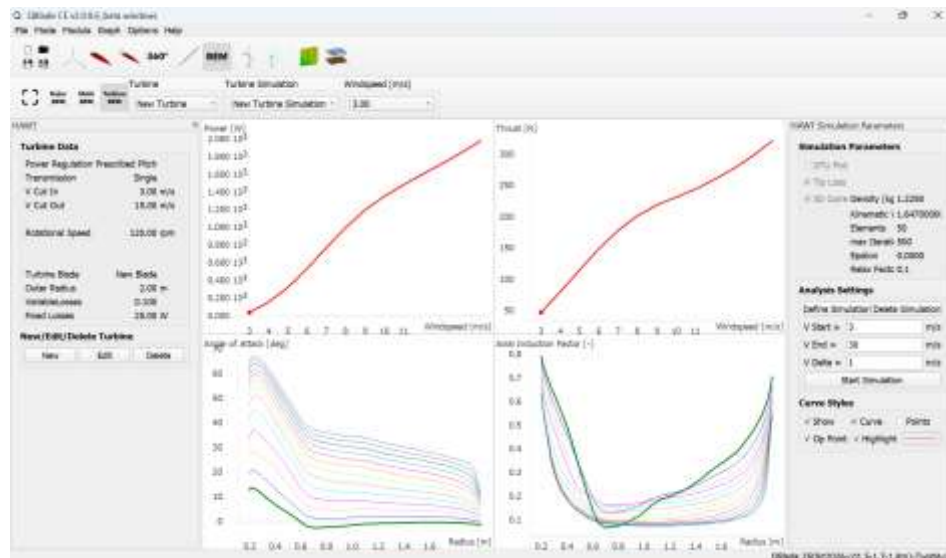


Figure 9. Turbine BEM Simulation with Prescribed Power Regulation

Figure 9 presents the simulation results for the Horizontal Axis Wind Turbine (HAWT) operating under a Prescribed Pitch power regulation strategy in QBlade. The setup maintains a constant rotational speed of 120.00 rpm, a cut-in speed ($V_{\text{cut-in}}$) of 3.00 m/s, a cut-out speed ($V_{\text{cut-out}}$) of 15.00 m/s, an outer rotor radius of 2.00 m, variable losses of 0.100, and fixed losses of 25.00 W.

The upper-left plot shows the mechanical power (P) as a function of wind speed (3 m/s to 12 m/s). The power curve grows continuously, reaching approximately 1.9×10^3 W (1.9 kW) at 12 m/s. Under the prescribed pitch schedule, power absorption increases smoothly across the evaluated wind speed domain. The upper-right plot depicts the axial thrust force (T), which rises steadily from around 50 N at 3 m/s to over 310 N at 12 m/s. This monotonic increase reflects the growing aerodynamic loading on the rotor disk as free-stream wind speeds escalate.

The lower-left plot displays the spanwise distribution of the Angle of Attack (α) along the blade radius (0.2 m to 1.8 m). Near the root section ($r \approx 0.2$ m), the angle of attack rises above 60° at higher wind speeds, while along the main span (0.6 m to 1.8 m), α is governed within a range of 0° to 35° according to the prescribed pitch angles. Lastly, the lower-right plot illustrates the Axial Induction Factor (a) across the blade radius. High induction values near the root ($r \approx 0.2$ m) and tip ($r \approx 1.8$ m) capture the expected loss phenomena, while the primary power-generating section ($0.6 \text{ m} \leq r \leq 1.6 \text{ m}$) remains stable within 0.08 to 0.30.

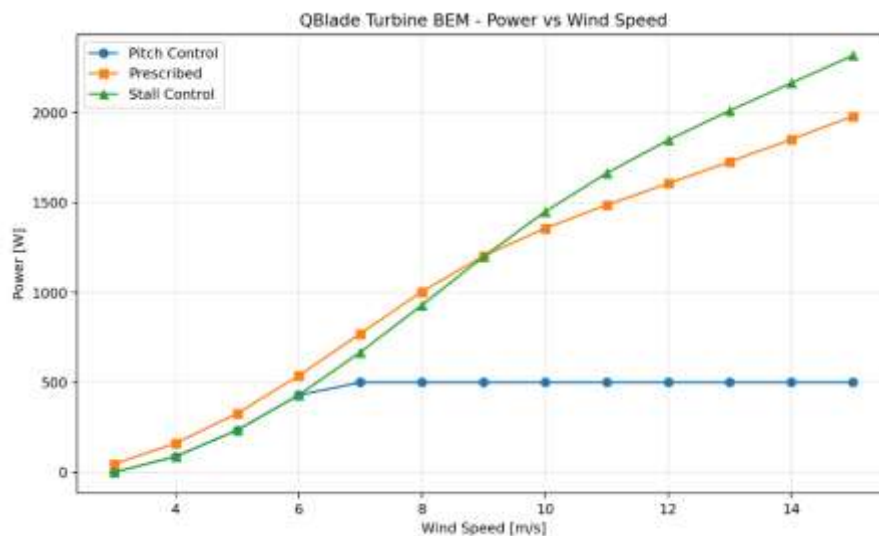


Figure 10. The Distinction Between Power Regulation of Pitch Control, Prescribed, and Stall Control

Figure 10 illustrates the differences between power regulation via pitch control, prescribed control, and stall control. The results show a clear distinction between Pitch Control, Prescribed, and Stall Control. At wind speeds of 3–6 m/s, all three methods yield relatively low power output, which increases as wind speed rises. At 6 m/s, Pitch Control and Stall Control produce 429.84 W, while the Prescribed method yields 538.18 W. From approximately 7 m/s onwards, the differences in characteristics become more significant. With Pitch Control, the power output is capped at around 500 W between 7 m/s and 15 m/s; this demonstrates that the strategy can maintain the generator's nominal power by limiting the increase in aerodynamic power through the adjustment of the pitch angle. In contrast, with the Prescribed method, power output continues to rise from 45.84 W at 3 m/s to 1,980.30 W at 15 m/s as this approach does not impose a 500 W power limit. Meanwhile, Stall Control exhibits characteristics similar to Pitch Control up to 6 m/s, but beyond 7 m/s, its power output exceeds 500 W, reaching 2,317.35 W at 15 m/s. This indicates that while Stall Control limits power increases passively via the aerodynamic characteristics of the blades, it fails to maintain the power output precisely at 500 W at higher wind speeds, unlike Pitch Control. Overall, Pitch Control is the most suitable strategy for a 500 W generator, as it allows power to increase with wind speed below the rated speed, while subsequently maintaining an output of approximately 500 W at higher wind speeds. From a system design perspective, these results suggest that the Prescribed method is better suited for describing power characteristics in the absence of specific limitations, whereas Stall Control serves as a simple alternative—requiring no active pitch mechanism though it results in power output significantly exceeding the rated value at high wind speeds.

Therefore, these simulation results demonstrate that the choice of power regulation strategy significantly influences the turbine's power characteristics. Pitch control provides the characteristics most consistent with the requirements of a 500 W power generation system, primarily due to its ability to limit power output once the nominal power level is reached. These findings also establish a foundation for further analysis regarding rated wind speed, cut-in/cut-out wind speeds, rotational speed, pitch angle, and the compatibility of the rotor's mechanical power with a 500 W electric generator.

4. CONCLUSION

The aerodynamic performance and predicted power characteristics of a 500 W-class small-scale horizontal-axis wind turbine (HAWT) were evaluated using Rotor BEM and Turbine BEM simulations in QBlade v2.0.8.6. The rotor achieved a peak power coefficient C_p of approximately 0.41 at a tip-speed ratio (TSR) of 5.0–6.0. Stall Control, Pitch Control, and Prescribed strategies were compared over wind speeds of 3–15 m/s, using a fixed pitch angle of 5° , a loss factor of 0.1, and fixed losses of 25 W.

At 6 m/s, the predicted power was 429.84 W for both Stall Control and Pitch Control, while Prescribed yielded 538.18 W. At 15 m/s, the predicted power reached 2,317.35 W for Stall Control and 1,980.30 W for Prescribed. In contrast, Pitch Control reached approximately 500 W at 7 m/s and maintained this level up to 15 m/s. These results indicate that the predicted power characteristics differ considerably among the three operating strategies, particularly at higher wind speeds.

Compared with the nominal generator rating of 500 W, Pitch Control exhibited the most suitable power-limiting characteristic among the three strategies under the simulated conditions. However, this finding does not establish its overall superiority in aerodynamic efficiency, electrical energy production, or total system performance. The 500 W rating served as a reference for comparison and was not automatically enforced as a power limit in every simulation. The higher predicted power under Stall Control and Prescribed indicates that the simulated turbine power can exceed the selected generator rating.

The reported results represent predicted turbine power rather than verified electrical output from the generator. Potential electrical power can be estimated under the assumed loss conditions; however, actual generator efficiency, converter losses, mechanical transmission losses, and other electrical losses may differ from these assumptions. Therefore, the estimated electrical power should be interpreted as preliminary rather than as confirmed generator output. Overall, the findings highlight the importance of considering power regulation when matching a small-scale wind turbine to a generator with a nominal rating of 500 W.

ACKNOWLEDGEMENTS

The authors would like to express their sincere appreciation to the QBlade development team for providing QBlade version 2.0.8.6, which was utilized in this study for the aerodynamic design and numerical analysis of the proposed 500 W small-scale horizontal-axis wind turbine. The software was used for airfoil analysis, blade geometry development, Blade Element Momentum (BEM) simulations, and turbine performance assessment under various operating conditions. The authors gratefully acknowledge the contribution of QBlade 2.0.8.6 to the numerical investigation presented in this work.

REFERENCES

- [1] D. A. Umar, C. T. Yaw, S. P. Koh, S. K. Tiong, A. A. Alkahtani, and T. Yusaf, "Design and optimization of a small-scale horizontal axis wind turbine blade for energy harvesting at low wind profile areas," *Energies*, vol. 15, no. 9, p. 3033, Apr. 2022, doi: 10.3390/en15093033.
- [2] A. Zarketa-Astigarraga, M. Penalba, A. Martin-Mayor, and M. Martinez-Agirre, "Impact of Turbulence and Blade Surface Degradation on the Annual Energy Production of Small-Scale Wind Turbines," *Wind Energy*, vol. 26, no. 12, pp. 1217–1234, Dec. 2023, doi: 10.1002/we.2866
- [3] G. T. Terefa, J. G. Njiri, P. I. Muiruri, and C. M. Abdissa, "Optimal design and analysis of a mixed airfoil blade for small-scale HAWTs," *Eng. Technol. Appl. Sci. Res.*, vol. 15, no. 3, pp. 22538–22547, Jun. 2025, doi: 10.48084/etasr.10275.
- [4] J. Radi and A. Djebli, "Optimal design of an horizontal axis wind turbine using blade element momentum theory," *E3S Web Conf.*, vol. 336, p. 00008, Jan. 2022, doi: 10.1051/e3sconf/202233600008.
- [5] G. Abad, A. Plaza, and G. Kerejeta, "Performance evaluation of small wind turbines under variable winds of cities: Case study applied to an Ayanz wind turbine with screw blades," *Smart Cities*, vol. 7, no. 6, pp. 3241–3288, Oct. 2024, doi: 10.3390/smartcities7060126.
- [6] A. Kumar, A. R. Tahasildar, A. S. Naidu, M. P. Sharun Divakar, and M. Suhail, "Design and analysis of horizontal axis small wind turbine for low wind velocity using QBlade," *J. Mines Met. Fuels*, vol. 71, no. 12, pp. 2554–2560, Dec. 2023, doi: 10.18311/jmmf/2023/36540.
- [7] O. K. Zidane and Y. H. Mahmood, "Small horizontal wind turbine design and aerodynamic analysis using Q-Blade software," *Baghdad Sci. J.*, vol. 20, no. 5, pp. 1772–1778, Oct. 2023, doi: 10.21123/bsj.2023.7418.
- [8] W.-G. Fröh, "Assessing the Performance of Small Wind Energy Systems Using Regional Weather Data," *Energies*, vol. 16, no. 8, Art. no. 3500, 2023, doi: 10.3390/en16083500.
- [9] S. Younoussi and A. Ettaouil, "Numerical Study of a Small Horizontal-Axis Wind Turbine Aerodynamics Operating at Low Wind Speed," *Fluids*, vol. 8, no. 7, p. 192, Jul. 2023, doi: 10.3390/fluids8070192
- [10] A. Rosato, A. Perrotta, and L. Maffei, "Commercial Small-Scale Horizontal and Vertical Wind Turbines: A Comprehensive Review of Geometry, Materials, Costs and Performance," *Energies*, vol. 17, no. 13, Art. no. 3125, 2024, doi: 10.3390/en17133125.
- [11] P. Strojny, "Study on the Efficiency of Small-Scale Wind Turbine with Rotor Adapted for Low Wind Speeds," *Bulletin of the Polish Academy of Sciences: Technical Sciences*, vol. 72, no. 6, Art. no. e151954, 2024, doi: 10.24425/bpasts.2024.151954.
- [12] M. Kulak, M. Lipian, K. Olasek, M. Pereira, and F. Ravelet, "Rotor solidity and blade pitch influence on horizontal axis small wind turbine performance – Experimental study," *Energy Reports*, vol. 12, pp. 4568–4577, 2024, doi: 10.1016/j.egyr.2024.10.036
- [13] M. A. Kadhim et al., "Performance Study of Low-Speed Wind Energy Harvesting by Micro Wind Turbine System," *Energy Reports*, vol. 13, pp. 3712–3727, 2025, doi: 10.1016/j.egyr.2025.02.046.
- [14] P. Mthethwa, T. S. Workneh, and A. Kassim, "Development of a Portable Small Wind Turbine for Integration into a Mobile Cooling Technology," *Sustainable Energy Research*, vol. 11, Art. no. 21, 2024, doi: 10.1186/s40807-024-00116-0
- [15] V. T. Signoretti, A. A. Simões Filho, R. L. P. Teixeira, R. F. Brito, and P. M. Guimarães, "Comparative Analysis of Aerodynamic Efficiency in Small-Diameter Wind Turbine Blades: NACA 4412 vs. Clark Y," *Revista de Gestão Social e Ambiental*, vol. 18, no. 2, Art. no. e07845, 2024, doi: 10.24857/rgsa.v18n2-200
- [16] M. E. Hasan, A. Eltayesh, M. I. Awaad, and H. M. El-Batsh, "Experimental Examination for the Electric Power Generation of a Commercial Small-scale Wind Turbine with Modified Aerodynamic Design," *Alexandria Engineering Journal*, vol. 64, pp. 25–39, 2023, doi: 10.1016/j.aej.2022.08.040
- [17] T. Aika, S. Igbinovia, and P. Orukpe, "Performance Evaluation of a Mini Permanent Magnet Synchronous Generator (PMSG) for Wind Energy System," *Journal of Engineering Studies and Research*, vol. 28, no. 3, pp. 22–28, 2022, doi: 10.29081/jesr.v28i3.002
- [18] T. Smaza et al., "Selecting the Best Permanent Magnet Synchronous Machine Design for Use in a Small Wind Turbine," *Electronics*, vol. 13, no. 10, Art. no. 1929, 2024, doi: 10.3390/electronics13101929
- [19] A. I. Altmimi, A. Aws, M. J. Jweeg, A. M. Abed, and O. I. Abdullah, "An Investigation of Design and Simulation of Horizontal Axis Wind Turbine Using QBlade," *Measurement Science Review*, vol. 22, no. 6, pp. 253–260, 2022, doi: 10.2478/msr-2022-0032.
- [20] W. K. Abbas, M. Abbasalizadeh, and S. Khalilarya, "Design optimization and performance investigation of a micro wind turbine for domestic dwelling used for renewable generation system," *Energy Sci. Eng.*, vol. 13, no. 6, pp. 3386–3409, Jun. 2025, doi: 10.1002/ese3.70109.
- [21] S. Iswahyudi, S. B. Wibowo, S. Suyitno, and A. Suprihanto, "Aerodynamic Performance and Noise Characteristics of Modified Blade Tip of Small HAWT," *Journal of Engineering and Technological Sciences*, vol. 56, no. 5, 2024, doi: 10.5614/j.eng.technol.sci.2024.56.5.8.