Wind Turbine Design for Low Wind Speed Applications: Advancing Renewable Energy Systems Through Wind Tunnel Experiments

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Abstract- The integration of wind energy into urban and rural energy systems presents a compelling pathway to sustainable energy generation. This study explores the design, optimization, and performance assessment of advanced wind turbine systems, emphasizing low wind speed applications and maximizing energy yield in varied geographical settings. Innovative methodologies such as computational fluid dynamics (CFD) and empirical performance testing underpin this research. The findings demonstrate enhanced energy efficiency through optimized blade designs and adaptive turbine configurations, addressing critical challenges such as turbulence and structural durability. This work contributes to advancing renewable energy technologies, offering scalable solutions for global energy sustainability.

Keywords: Wind Turbine Design, Renewable Energy Systems, Low Wind Speed Application, Energy Efficiency. Wind power.

I. Introduction

The global shift towards sustainable energy has made wind power a key player in combating climate change and reducing fossil fuels. Although wind turbines are crucial for harnessing this abundant resource, they nonetheless face challenges, even in low-wind locations. Novel technical solutions are needed to address limitations such low energy capture efficiency, turbulence, and structural stability. Wind tunnel testing and blade design optimization are crucial for wind turbine development. Wind tunnels have gained attention for their ability to simulate real circumstances and optimise turbine design. Dr. Ulan Dakeev's study found that wind tunnel attachments increase energy output under different scenarios (Dakeev, 2011). Allen Pope's low-speed wind tunnel research (Pope, 1999) has advanced turbine aerodynamics knowledge. Singh and Ahmed (2013) highlighted the benefits of optimised blades for small wind turbines, while Ozbay (2018) provided insights into turbine aerodynamics and wake interferences. The Virtual Blade Model by Bianchini et al. (2012) is effective for wake analysis, whereas Saidur et al. [4] examined the environmental advantages of wind generation. However, a thorough understanding of how blade number (two or three) impacts energy capture performance is lacking, particularly for low wind speeds. This study addresses the gap by comparing two and three-blade wind turbines and analysing their energy generation under controlled conditions. The goal is to improve wind energy system design and optimisation for rural and urban locations by tackling low wind speed circumstances.

Fig 1: Wind turbine

The kinetic energy of the wind can be transformed into mechanical or electrical power by means of wind turbines, the most common of which are horizontal-axis (HAWT) and vertical-axis (VAWT). The most popular kind, HAWTs, maximize efficiency by aligning with the direction of the wind, whereas VAWTs, which are better suited to turbulent or urban areas, work independently of the wind direction. Larger turbines enable grid-scale power production, whether on land or at sea, while smaller ones are utilized for tasks such as water pumping or household electricity. Wind turbines as shown in the fig. 1, are clean and emit few pollutants, yet they nonetheless have their share of problems, including noise, environmental hazards (such as bird collisions), and unpredictable production. They are becoming more efficient and dependable as a result of technological developments like as better blade design,

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grid integration tactics, and energy storage. Aeronautical settings, such as those at high altitudes or in cold climates where anti-icing and aerodynamic performance are paramount, are finding more and more uses for wind power, which is a significant renewable energy source overall.

II. Methodology

Wind turbine blade optimization for low wind speeds was experimentally approached by Singh and Ahmed (2013), who developed a two-bladed rotor using the low Reynolds number AF300 airfoil with tapered and twisted geometries tested at 15°, 18°, and 20° pitch angles. Field trials on an Air-X marine 400 W turbine (3–6 m/s wind speeds) demonstrated superior performance over a baseline three-bladed rotor. In parallel, Dakeev (2011) enhanced turbine power output via a custom wind tunnel attachment, statistically validating improvements at a 95% confidence level through characteristic performance curves. On the simulation side, Bianchini, Balduzzi, and Ferrari (2012) employed a Virtual Blade Model (VBM) integrated into ANSYS FLUENT, combining RANS equations with blade element theory to efficiently model wakes, validated against NOWITECH-NORCOWE experimental data. Ozbay (2018) further examined turbine aeromechanics and wake interactions using Iowa State's AABL wind tunnel, capturing detailed flow fields with PIV and cobra probes across varied terrain topographies, yaw angles, and turbulence conditions, complemented by electrical performance tests in a low-speed supersonic tunnel.

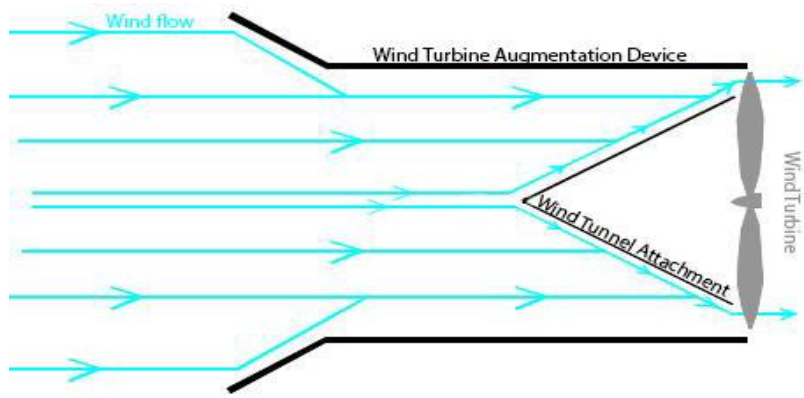

Fig 2: Cross section of wind tunnel

Turbine Blades Design

The ratio between the speed of the blade tips and the speed of the wind is called tip speed ratio. High efficiency 3-blade-turbines have tip speed/wind speed ratios of 6 to 7. Modern wind turbines are designed to spin at varying speeds (a consequence of their generator design, see above). Use of aluminum and composite materials in their blades has contributed to low rotational inertia, which means that newer wind turbines can accelerate quickly if the winds pick up, keeping the tip speed ratio more nearly constant. Operating closer to their optimal tip speed ratio during energetic gusts of wind allows wind turbines to improve energy capture from sudden gusts that are typical in urban settings.

In contrast, older style wind turbines were designed with heavier steel blades, which have higher inertia, and rotated at speeds governed by the AC frequency of the power lines. The high inertia buffered the changes in rotation speed and thus made power output more stable.

It is generally understood that noise increases with higher blade tip speeds. To increase tip speed without increasing noise would allow reduction the torque into the gearbox and generator and reduce overall structural loads, thereby reducing cost. The reduction of noise is linked to the detailed aerodynamics of the blades, especially factors that reduce abrupt stalling. The inability to predict stall restricts the development of aggressive aerodynamic concepts. Some blades (mostly on Enercon) have a winglet to increase performance and/or reduce noise. A blade can have a lift-to-drag ratio of 120, compared to 70 for a sailplane and 15 for an airliner.

Blade Materials

Modern wind turbine blades use advanced fiber-reinforced composites, especially carbon-fibre girders, to balance strength, rigidity, and weight. A blade material should be easily available, easy to make, low-density to reduce gravity, and high-mechanical strength to endure airflow and self-load. Materials must be rigid enough to maintain blade geometry and tower clearance and fatigue-resistant enough to sustain billions of load cycles over a turbine's 20-year lifespan. Fracture toughness is essential in addition to resistance to dampness, lightning, and extreme temperatures. Blade construction has evolved from wood and cloth to metals and plastics. Composite materials were chosen due to metal fatigue and polymer flexibility. Design optimisation methods like HyperSizer allow engineers to improve energy extraction while addressing scaling structural restrictions. Modern turbine blades can surpass 170 meters in length. Structural engineering and materials science have improved wind turbine size, durability, and efficiency, making them a better renewable energy source.

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Experimental Setup

The dynamo motor that was used for the tests had a motor shaft that was 2 millimetres in diameter, was 30 millimetres in length, weighed 150 grammes, and rotated at 1200 revolutions per minute. Within the wind tunnel test section, the blade of the wind turbine is securely attached to the motor shaft and positioned as shown in the fig. 2. For the purpose of ensuring the blade's structural integrity, a steel rod is used to reinforce it. During the installation process, a multi-meter is employed in order to evaluate the amount of electrical output that is generated by the turbine. There is a spectrum of input wind velocities, and output power is measured throughout that spectrum in order to quantify performance variances as shown in figure 3 and figure 4. These measurements are used to generate a characteristic performance curve, which is then used to evaluate the efficiency of the turbine under a variety of different operating conditions.

The experiments were conducted in a low-speed wind tunnel with a maximum wind speed of 50 m/s. The test section of the wind tunnel measured 60 cm × 60 cm × 2 m, providing a stable environment for assessing turbine performance. Wind speed was measured using a calibrated anemometer, and the velocity was controlled using a variable speed controller. To ensure consistency, each test was conducted multiple times under identical conditions, with careful monitoring of environmental factors to maintain repeatability.

Fig 3: Experimental set-up of three blade profile

Fig 4: Experimental set-up of two blade profile

Table 1: Geometry Details

Details	**TWO BLADE**	**THREE BLADE**
Length	12*3*1	7.5
Thickness	5mm	2mm
Diameter	13mm	13mm

This study determined an optimal performance configuration for the two and three-blade wind turbine designs through systematic experimental analysis. Although advanced optimization techniques (such as computational fluid dynamics or multi-objective optimization) were not used in this study, these methods can be explored in future work to further enhance turbine performance.

III. Results

1.Power output obtained for three blade wind turbines when tested in wind tunnel at different wind velocities (0degree, 10degree, 20degree, 30degree, 35degree, 40degree, 50degree,60degree) are represented in tabular column, The graphical representations of various output power for the above values will be shown in below figure

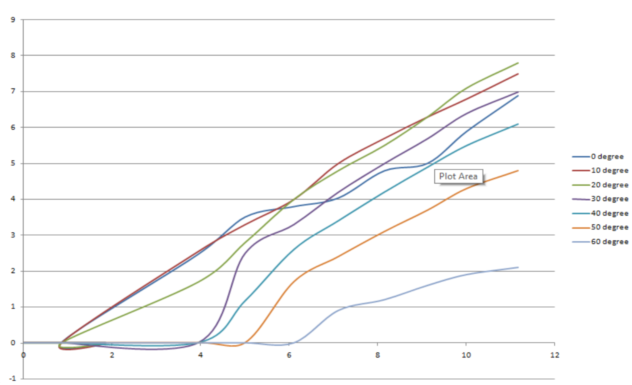

Fig 5: Graphical representation of velocity vs power for three blade profile with positive wind velocity angles

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2.Power output obtained for three blade wind turbine when tested in wind tunnel at different wind velocities (-10degree, -20degree, -30degree, -35degree, -40degree, -50degree,-60degree) are represented in tabular column. The graphical representations of various output power for the above values will be shown in below figure

Velocity	0 degree	10 degree	20 degree	30 degree	35 degree	40 degree	50 degree	60 degree
0	0	0	1.25	0	0	0	0	0
1.84	1.64	1.6	2.66	0	0	1.31	0	0
2.85	3.38	3.27	3.95	2.23	1.64	2.63	2.16	0
3.94	5.3	4.76	5.3	4.42	2.52	3.86	3.18	0
5	6.95	6.24	6.4	5.45	3.35	5.03	4.2	0
6.1	8.45	7.64	7.55	6.5	4.11	6.19	5.09	0
7.12	9.75	8.94	8.6	7.46	4.94	7.36	6.12	0
8.14	10.9	10.05	9.52	8.35	5.64	8.42	7.11	0
9.12	11.94	11.17	10.05	9.24	6.56	9.36	7.95	0
10	12.88	12.15	11.95	10.08	7.33	10.22	8.76	0
11.6	13.68	13.02	13.04	11.03	8.06	11	9.55	0

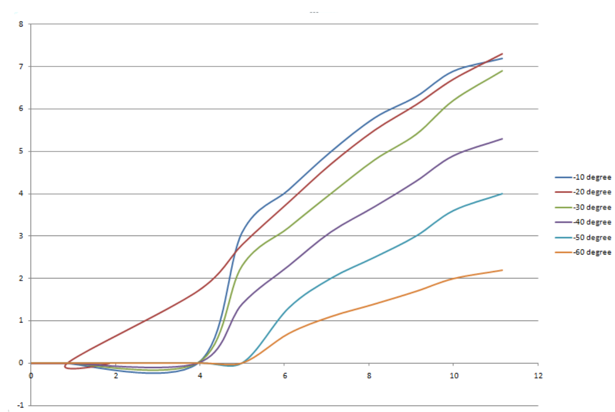

Fig 6: Graphical representation of velocity vs power for three blade profile with negative wind velocity angles

3.Power output obtained for two blade wind turbine when tested in wind tunnel at different wind velocities(0degree, 10degree, 20degree, 30degree, 40degree, 50degree, 60degree) are represented in tabular column. The graphical representations of various output power for the above values will be shown in below figure

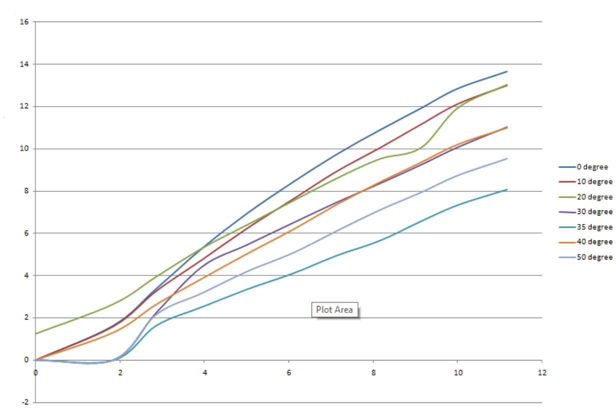

Fig 7: Graphical representation of velocity vs power for the two-blade profile with positive wind velocity angles

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4.Power output obtained for two blade wind turbine when tested in wind tunnel at different wind velocities (-10degree, -20degree, -30degree, -40degree, -50degree, -60degree) are represented in tabular column. The graphical representations of various output power for the above values will be shown in below figure

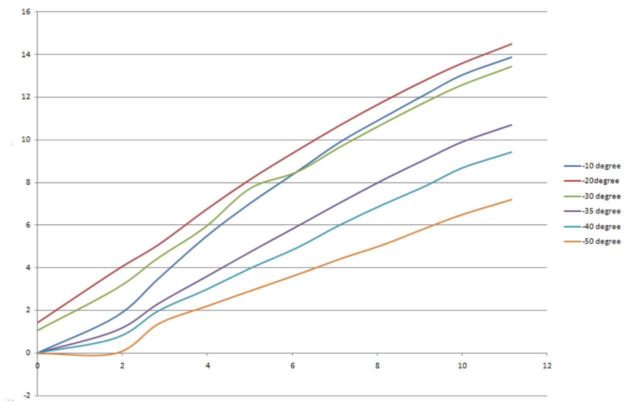

Fig 8: Graphical representation of velocity vs power for the two-blade profile with negative wind velocity angles

Expanded Performance Analysis

Enhanced Efficiency and Analysis of Variance

Three crucial performance metrics, namely TSR, Cp, and η, were identified to provide a comprehensive evaluation of the turbine's efficiency. This information is helpful for understanding the aerodynamic performance of turbine blades, and it was derived from the ratio of blade tip speed to wind velocity. The conversion efficiency is reflected in Cp, which is determined by the real power production and the highest possible wind power. Last but not least, efficiency was defined as the ratio of mechanical power intercepted by the blades to the electrical output power. There was a comparison of the two-blade and three-blade configurations' performances.

The power-performance comparison was done for various wind-speed scenarios, and it showed that two-blade and three-blade rotors are fundamentally different. In order to make an appropriate assessment of electrical performance, we additionally evaluated power-conditioning, conversion efficiency, and generator load characteristics. Without taking into account advanced parameters like aerodynamic stability, noise, or cost, it would be possible to comprehend the operational performance of each arrangement in this way.

Comparative Analysis of Two-Blade and Three-Blade Configurations

This study focuses on a direct comparison of power output between two-blade and three-blade wind turbines. The analysis presents power output at various wind speeds, highlighting the differences in performance between the two configurations. Power conditioning, efficiency of conversion, and generator load characteristics were also monitored to ensure accurate assessment of electrical output.

IV. Conclusion

This paper offers a thorough evaluation of the aerodynamic and energy conversion performance of two-blade and three-blade wind turbine layouts under low wind speed situations, based on a rigorous experimental investigation. Over a wide range of wind speeds, the results show that the three-blade design achieves better power coefficients (Cp) and efficiency values, making it the superior design in terms of power production. Results like these provide light on how to best arrange wind turbine blades for maximum efficiency. Computational Fluid Dynamics (CFD) simulations could greatly improve future research, even if this study is based on empirical data. To better understand the turbines' aerodynamic behaviour and optimise their efficiency, such models would allow for in-depth research of flow properties, pressure distributions, and vortex interactions surrounding the blades. Improved turbine performance may be possible with the use of computational fluid dynamics (CFD) to test out new control systems, fine-tune blade designs, and increase energy capture.

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