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Studying, Simulation and Analysis of a Small-Scale Horizontal Axis Wind Turbine Using MATLAB and Ansys

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Abstract- Wind energy has been one of the most essential parts of the trend of moving towards cleaner, more sustainable energy systems. This is mainly because of two primary reasons, reducing CO2 emissions and secure energy production. Unlike conventional large-scale, carbon-intensive power plants, modern wind farms provide noticeable reductions in greenhouse-gas emissions and enhanced energy security by harnessing an abundant natural resource: the wind. Among various models and configurations of wind turbines, Horizontal Axis Wind Turbines (HAWTs) are the most dominant in wind energy applications. This is primarily because they are the most efficient, the most scalable, and the most mature in terms of their technology. The study gives the reader a structured overview of the advancement, performance, and design features of HAWTs in this literature review. The work presents the main topics of standardized aerodynamic blade design, the operation of the elements of the control mechanism, and possibilities of the improvement of the efficiency of the wind system. Additionally, in the document the comparison between the two types, Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs), is carried out to show the advantages and limitations of HAWTs. This review identifies the current challenges as well as the possible future development in the wind energy sector, through a deeper analysis of recent research and technical improvements.

Keywords- Wind turbine, Wind speed, Modeling, Simulation, Renewable energy

I. INTRODUCTION

The global energy landscape has shifted significantly due to the environmental, economic, and societal concerns associated with fossil fuel consumption and traditional power generation. As a result, governments, utilities, and private investors are increasingly turning toward renewable alternatives.

Among these, wind energy has proved its importance, thanks to its vast resource potential, relatively low lifecycle costs, and minimal environmental footprint. Modern wind farms, both onshore and offshore, can now deliver utility-scale power at competitive prices. Advances in turbine design such as longer, lighter blades made from advanced composite materials, variable-speed generators, and advanced control systems have cut down the levelized cost of energy (LCOE) by more than 70 percent over the past two decades.

As a result, wind energy now possesses an increasing share of electricity generation in markets across Europe, North America, Asia, and beyond. In addition, the quick scalability of wind energy changing regional and national energy planning. With the increasing popularity of hybrid systems that include wind, solar photovoltaics, battery storage, grids can now handle higher levels of intermittent renewable energy sources. At the same time, floating offshore wind systems make use of stronger, more consistent winds in deepwater zones, opening up new opportunities for development.

Social acceptance has also improved as people started to recognize wind power's benefits including reduced air pollution, creating new jobs in manufacturing and maintenance, and the potential for local ownership models that keep revenue within rural economies. Despite challenges such as visual impact concerns and wildlife interactions, ongoing research into quieter blade designs, radar-friendly coatings, and monitoring systems aims to solve these issues. Wind-powered ships, grain mills, water pumps, and threshing machines are all examples of harnessing wind power from early ages. With the evolution of mechanical engineering and technology, the last decades of the 20th century saw the development of machines which efficiently generate power from wind. "Wind turbines" is now being used as a generic term for machines with rotating blades that convert the kinetic energy of wind into useful power. In the 20th century, early wind turbine designs were driven by three basic philosophies for handling loads:

- Withstanding loads
- Shedding or avoiding loads
- Managing loads mechanically, electrically, or both.

During this evolution, many wind turbine designs we developed, including horizontal axis and vertical axis turbines. Turbines that spin around horizontal and vertical axes, respectively, and are equipped with one, two, three or multiple blades. Modern turbines can be classified as two or three-bladed turbines with horizontal axes and upwind rotors. Today, the choice between two or three-bladed wind turbines is merely a matter of a trade-off between aerodynamic efficiency, complexity, cost, noise and aesthetics. Additional key turbine design considerations include wind climate, rotor type, generator type, load and noise minimization, and control approach. Moreover, current trends, driven by the operating regime and the market environment, involve the development of lowcost, megawatt-scale turbines and lightweight turbine concepts. Whereas turbines operating at constant rotor speed have been dominating up to now, turbines with variable rotor speed are becoming increasingly more common to optimize the energy capture, lower the loads, obtain better power quality, and enable more advanced power control aspects.

A wind turbine converts wind's kinetic energy into mechanical energy, which is then transformed into electrical power using a generator. The turbine system typically consists of three major components:

- The rotor (with blades that capture wind energy)
- The gearbox (which transfers mechanical energy from the low-speed shaft to the highspeed shaft)
- The generator (which produces electricity).

These components work together in a coordinated kinematic chain, which can be modelled and analysed using simulation tools like MATLAB/Simulink. These simulations offer numerical data and help visualize how different factors, such as wind speed and blade pitch angle, affect power output and efficiency.

It is essential to understand wind characteristics such as direction and speed for maximizing turbine efficiency. Even minor fluctuations in these parameters can significantly affect a turbine's power output and may cause voltage and current fluctuations in the electrical network.

Conceptual Aspects

Early wind machines sometimes used many short blades arranged around the hub. In these multi-bladed designs, the total blade area facing the wind, called the rotor's solidity, was quite large compared to the circle the blades swept out as they turned.

While high solidity meant the turbine could start turning in very light breezes, it also made the rotor catch huge forces during extreme gusts or storms. For example, in case of a hurricane, all those extra blades would slam into the wind like a giant sail, putting very high stress on the tower and gearbox.

To avoid those problems and enhance overall efficiency, today's turbines use far fewer blades, usually just three, that are long and narrow. This low-solidity approach reduces the wind-loading in storms and largely decreases drag at normal speeds. Because these thinner blades catch less wind area, wind turbines spin much faster, where the blade tips can whip around at many times the wind speed. Faster rotation helps the lean profile capture more energy despite its slim shape.

Over time, engineers have developed blade materials and shapes to handle these high tip-speed stresses. Lightweight composites, like fiberglass and carbon fiber, give blades the strength they need without making them too heavy. Aerodynamic tuning such as twisting the blade slightly from root to tip, adding winglet-style edges, or smoothing the surface, further enhance the performance by keeping airflow attached and reducing drag. Combined with advanced controls that adjust blade angle in extreme winds, these innovations allow modern turbines to convert more of the wind's power into electricity while withstanding any environmental or weather conditions.

- **Vertical Axis Turbines**

Vertical axis wind turbines (VAWTs), such as the one shown in Figure 1 with C shaped blades, are among the types of turbines that have been developed greatly in the past century.

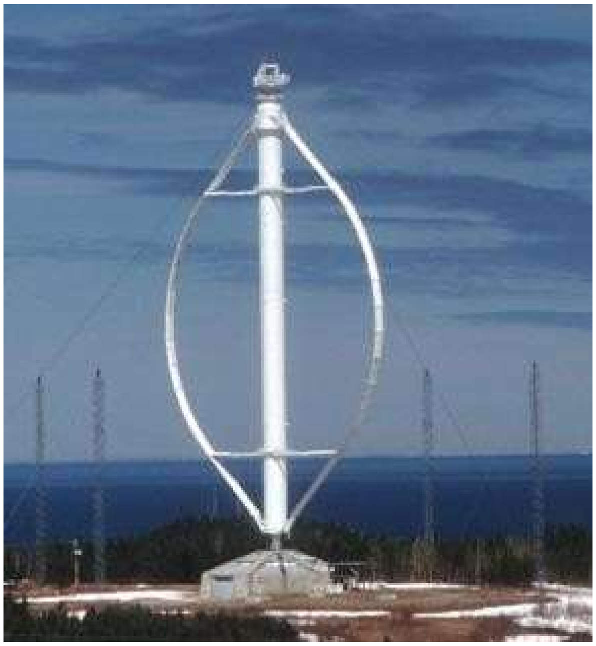

Fig 1. Eole C, a 4200-kW vertical axis Darrieus wind turbine with 100 m rotor diameter at Cap Chat, Québec, Canada. The machine, which is the world's largest wind turbine, is no longer operational. Danish Wind Turbine Manufacturers Association.

Classical water wheels are designed so that the water flows tangentially to the rotational axis of the wheel. Vertical axis wind turbines are designed to interact with air in a similar way. While this could be applied to a horizontal axis turbine, it would require a more complex design, which would probably be less efficient than a propeller-style turbine. The primary advantages of vertical axis wind turbines include the placement of the generator and gearbox on the ground, making them more accessible for maintenance, and the absence of a yaw mechanism, which simplifies the design. This can be especially beneficial in environments where regular maintenance is necessary and turbine orientation adjustments are not required. However, these turbines have several drawbacks. They generally have a much lower efficiency than their horizontal axis counterparts, require the entire turbine to be dismantled for main bearing replacement, and the rotor is situated relatively close to the ground, where wind speeds are typically lower.

- **Horizontal axis turbines**

Horizontal axis wind turbines (HAWTs), such as the ones shown in Figure 2, are the most common type of wind turbine used today. In fact, all grid connected commercial wind turbines are today designed with propeller-type rotors mounted on a horizontal axis on top of a vertical tower. Unlike vertical axis turbines, horizontal axis turbines need to be aligned with the direction of the wind, allowing the wind to flow parallel to the axis of rotation.

Fig. 2 : Wind turbines at the Post Rock wind facility near Ellsworth, Kansas. Credit: Brian Grimmett/Kansas News Service.

When discussing horizontal axis wind turbines, a major difference exists between upwind and downwind rotors, each with unique design characteristics and performance. Upwind rotors, positioned in front of the vertical tower, are designed to face the wind. This arrangement helps reduce the wind shade effect, which occurs when the tower blocks the wind's direct flow to the rotor, enhancing the turbine’s ability to capture wind energy. However, upwind rotors require an active yaw mechanism to continuously align the rotor with the changing direction of the wind, ensuring optimal performance.

In contrast, downwind rotors are positioned on the lee side of the tower, where they experience a more turbulent airflow. This setup leads to significant challenges, particularly the fluctuating wind power as the rotor passes through the turbulent wake created by the tower. These fluctuations increase fatigue loads on the turbine, reducing the efficiency of the system and potentially shortening the lifespan of the components. While it is theoretically possible to design a downwind rotor without a yaw mechanism, this requires careful consideration of the rotor and nacelle design to ensure that the nacelle can passively align with the wind. However, this passive yawing can generate gyroscopic forces, creating additional stresses. Over time, the rotor's constant rotation in the same direction could cause the cables to twist, leading to difficulties in unwinding them, which is a big problem in large turbines.

The issue of twisting cables in downwind systems further complicates the use of slip rings or mechanical collectors to manage the power transmission, especially in large-scale turbines. On the other hand, the structural demands of upwind rotors require them to be relatively inflexible in order to maintain sufficient clearance from the tower, preventing interference between the blades and the structure. In contrast, downwind rotors can be made more flexible, potentially offering weight-saving advantages and reducing the loads on the tower. Despite the theoretical benefits of downwind rotors, most wind turbines in operation today continue to use upwind rotor designs due to their better performance in terms of efficiency, load management, and overall system reliability.

- **Number of rotor blades**

Most wind turbines spinning above fields or offshore have three blades. There is a reason for this: three blades strike a sweet spot between grabbing enough wind, keeping costs reasonable, and spinning smoothly without too much vibration.

Fig. 3 Three, two and one-bladed wind turbine concepts.

A particular style called the "Danish concept" has become the gold standard. The blades sit out in front of the tower (upwind), are driven by a simple induction generator, and are gently aligned with the breeze by an active yaw system. Engineers appreciate this design for its reliable performance and affordability over many years.

Designers have experimented with two or even one blade layouts to reduce weight and cost. The catch is that with fewer blades, the rotor must spin faster or feature much wider blades to capture the same amount of wind. Faster spinning can create more noise, and wider blades may look awkward against the skyline.

Fewer blades also lead to more dramatic shifts in balance as each blade moves through its arc. A blade at the top of its rotation experiences a different load than when it reaches the bottom or encounters a sudden gust. To soften these jolts, many two and single blade turbines incorporate a teetering hub—a hinge at the rotor's heart. This hinge allows the rotor to tilt slightly, evening out the bumps and protecting both tower and gearbox from wear and tear.

Even so, one blade turbines are rare. Beyond the need for very high rotational speeds, which can increase noise, a single blade design requires a heavy counterweight on the opposite side to maintain balance. Two blade versions avoid some of that complexity and extra ballast while remaining simpler than a single blade setup.

Using fewer blades can save money and reduce rotor weight. But with fewer blades you need to spin faster or make each blade wider (a larger chord) to catch as much wind as a three-blade turbine of the same size. Faster spinning also creates more noise, and wider blades can look ungainly, so there's a trade-off between cost and performance.

Another challenge with one or two-blade rotors is the way the weight and inertia shift as blades move around. When a blade is at the top or bottom of its rotation, or when wind speed changes mid-sweep, the forces on the hub can fluctuate a lot. To manage these uneven loads, most one- and two-blade turbines use a "teetering hub" which is a hinge that lets the whole rotor tilt slightly. That hinge smooths out some of the imbalances and protects the gearbox and tower from stress and possibly failure.

Even so, one-blade turbines are rare compared to two-bladed models. In addition to needing higher rotational speeds (which can cause more noise and stress), a single-blade design must include a heavy counterweight on the opposite side of the hub to stay balanced. Two-blade designs still require careful balancing and teeter hubs, but they avoid the complexity and extra weight that a one-blade system demands.

2. Configurations and sizes

Wind turbines can be installed as individual units, grouped in clusters of multiple turbines, or, in larger configurations, organized into wind parks or wind farms. Prior to the 1980s, the primary focus of wind energy development was on optimizing individual turbines. However, by the late 1980s, the approach evolved, shifting toward the collective generation of electricity from an array of turbines situated near one another, forming what are now commonly known as wind parks or wind farms.

In the early 1980s, the typical wind turbine had a rated power of around 55 kW, but over the years, turbine capacities have significantly increased, with modern turbines now exceeding 2 MW in rated power. This significant growth in turbine size has been accompanied by advancements in rotor design, which are optimized for varying tower heights. These developments have greatly expanded the capacity and efficiency of wind power generation, enabling turbines to operate effectively in a wider range of environmental conditions.

Table 1 Typical wind turbine sizes.

Tower Height (m)	Rotor Diameter (m)	Rated Power (kW)
22	21	55
31	30	225
35	35	450
35-40	41-44	500
44	43	600
50	48	750
50	54	1000
60	58	1500
64-80	72-76	2000
85	115	5000

While wind energy has already become economically viable in onshore locations with strong, consistent wind patterns, the focus is now shifting toward offshore wind energy. Offshore wind farms are becoming more competitive, particularly in regions where land availability for wind turbines is limited due to high population densities. Although construction costs for offshore wind farms are considerably higher than their onshore counterparts, the energy production potential is also much greater, making these projects economically viable in certain regions.

Fig. 4: Vindeby Offshore Wind Farm. From www.windpower.org (1997) © Bonus.

At present, the installation of wind turbines on fixed foundations in water depths of up to 15 meters is considered economically feasible. This development opens new opportunities for harnessing wind energy in coastal areas, where the wind is typically stronger and more consistent than on land. Despite the challenges involved in offshore construction, including the need for specialized infrastructure and higher initial investment costs, offshore wind energy is viewed as a promising application for countries with limited land for onshore projects. An example of an early offshore wind farm illustrates the potential for large-scale energy generation in marine environments, further advancing the role of wind energy in the global power mix.

3. Future Concepts

So far, the development of large wind turbines has mainly focused on scaling up existing, widely adopted designs. However, the continuous growth of wind energy demands innovative thinking, and new concepts for turbine designs and components are actively being explored to meet these needs. One future direction involves creating wind turbines that are more flexible at various levels. One significant aspect of this future development is the anticipated increase in structural flexibility. The idea is to design turbines with materials and structures that allow for controlled bending or movement, especially in response to gusty winds or sudden changes in wind direction. By permitting parts like blades, hubs, and towers to flex, the turbines could reduce mechanical stress, minimize fatigue, and extend their lifespan. This flexibility would allow the turbine to absorb gusts more gently, much like a tree swaying in the wind, rather than withstanding high levels of stress that could lead to failure.

In addition to more flexible structures, the drive train which is responsible for converting the wind's mechanical energy into electrical power, could become more adaptable. One possible development is the shift from traditional gearboxes to direct-drive, gearless systems. These systems would use variable speed generators, paired with advanced power electronics, to adjust the turbine's rotational speed based on wind conditions. This setup would not only optimize the turbine's performance but also reduce mechanical complexity, lower maintenance costs, and improve efficiency by enabling the turbine to run more smoothly at varying speeds.

Using power electronics is expected to increase as well. These electronic systems, which manage the turbine's electrical output, could become more advanced, using real-time monitoring and precise control to ensure most efficient operation. The integration of semiconductors and modular converters could lead to even more efficient power conversion, providing better control over the turbine's output and responding more effectively to changes in wind speed.

Furthermore, adaptive control systems will likely become more common, with turbines relying on a network of sensors to constantly monitor various conditions, including wind speed, blade deflection, vibrations, and environmental factors like lightning strikes. These sensors will feed data into processors, which could adjust the blade pitch, yaw alignment, and power generation in real time. With machine learning, these systems might even predict potential failures before they occur, allowing for proactive maintenance and minimizing downtime.

As wind turbine technology advances, the focus may shift from controlling individual turbines to managing entire wind farms as integrated systems. Instead of each turbine operating independently, turbines could coordinate their actions with others in the farm to optimize performance. This could involve adjusting their wind wake patterns or power outputs to minimize wake effects, smooth out fluctuations in power generation, and improve overall efficiency. However, this shift would demands individual turbines to communicate more effectively, respond dynamically to changes in the system, and be more adaptable to the farm's needs.

II. METHODOLOGY

Given the challenges and complexities associated with real-world testing, wind turbine systems are often analysed through simulation tools, such as MATLAB/Simulink. These simulations offer crucial insights into the mechanical, aerodynamic, and control system behaviour under various operating conditions, providing a valuable means of understanding turbine performance before physical testing.

This paper specifically focuses on the modelling and simulation of a small-scale wind turbine system which is a 300-W horizontal-axis wind turbine (ATO-WTS300). The primary goal of this study is to examine its aerodynamic performance, mechanical torque characteristics, and response to varying wind conditions and pitch angles. Small and medium-sized wind turbines, like the 300-W model, are becoming increasingly significant for decentralized power generation. These systems are particularly beneficial in rural and off-grid areas, agricultural applications, and industrial facilities, providing an efficient and sustainable solution for energy generation on a community or facility scale. Such turbines offer a practical middle ground between large, utility-scale wind farms and smaller, household-scale wind systems, meeting the energy needs of these sectors.

Through this study, which applies detailed simulations of the turbine's behaviour, the research aims to enhance the understanding of its characteristics. The goal is to identify key factors that can be optimized to improve the turbine's reliability

and energy output in real-world environments. By examining these variables in a controlled, simulated setting, it is possible to predict the turbine's performance under diverse conditions before actual deployment.
The turbine's electrical output is directly influenced by both the wind's velocity and the angle of attack. As the wind speed fluctuates, the performance characteristics of the turbine, including the torque applied to the rotor, will change accordingly. These variations are critical in determining how the turbine responds to dynamic environmental conditions, affecting overall efficiency and stability. This research aims to provide valuable data that could inform design improvements, control strategies, and operational practices to maximize the effectiveness of small-scale wind turbines.

1. Wind Turbine Specifications and Simulation Inputs

The MATLAB simulation was performed using technical specifications of a small-scale horizontalaxis wind turbine model (ATO-WT-S300). The following parameters were used throughout the study:

Table 2: Table of Parameters Used in the Simulation.

Parameter	Symbol	Value	Unit	Notes
Blade radius	R	0.675	m	Correspond s to 1.35m diameter
Air density	ρ	1.225	kg/m^3	——
Pitch angles	β	0, 5, and 10	Deg.	selected to analyse blade aerodynami c response
Generator efficiency	η	0.85	——	typical for small-scale systems
Rotor inertia	J	2.5	$kg{\cdot}m^2$	estimated based on rotor mass & geometry
Rated electrical power	——	300	W	——
Maximum allowable power	——	320	W	safety threshold
Cut-in wind speed	——	2.5	m/s	——
Rated wind speed	——	11.5	m/s	——
Cut-out wind speed	——	50	m/s	shutdown limit to avoid structural damage
Number of blades	——	3	——	standard for small HAWT

These inputs were implemented in MATLAB as parameter definitions for aerodynamic power calculations, torque modelling, and simulations of the rotor under variable wind conditions.

2. Governing **Equations**

To find out how the wind turbine performs its function, a series of fundamental concepts about power, torque, and the general efficiency of the system were used. This is the basis for understanding the simulation.

2.1. Wind Speed Profile Modeling To estimate wind speed at hub height, the logarithmic power law is used:

$$v(z) = v_{ref}\left(\frac{z}{z_{ref}}\right)^{\alpha} \quad (1)$$

Where:

- v(z) is the wind speed at hub height z
- $vref$ is the wind speed at reference height zref =10m

- α is the wind shear exponent (typically 0.14 for open terrain)

To simulate realistic wind profiles, turbulence is added using Gaussian-smoothed random noise:

$$vturb = v(z)(1 + I * smoothed\ noise) \quad (2)$$

Where: I is the turbulence intensity.

2.2. Mechanical Power Extraction

A turbine converts the energy captured from moving air into electrical energy. The following equations describe the power coefficient, air density, and turbine swept area as variables that affect the captured energy

$$P_{mech} = 1\_\ \rho A C_P(\lambda, \beta) v^3 \quad (3)$$

The equation represents the power produced by the wind (Pm) in watts. It involves variables such as the density of air (ρ), which is 1.225 (kg/m3), coefficient of power (Cp) as a function of tip speed ratio (λ) and pitch angle (β), wind velocity (v) in meters per second, and the swept area (A) in square meters.

Where:

- A= πR2 is the swept area
- Cp is the power coefficient, defined as:

$$C_P(\lambda, \beta) = 0.25\left(\frac{100}{\lambda} - 0.5\beta - 4\right) exp\left(\frac{-10}{\lambda}\right) \quad (4)$$

The electrical power output is calculated by:

$$\mathbf{Pelec} = \eta \mathbf{Pmech} \quad (5)$$

, with saturation at rated and maximum power

$$\mathbf{Pelec} = 0,\ if\ v < \mathbf{vcut{-}in\ or}\ \ v > \mathbf{vcut{-}out}$$

$$= min(\mathbf{Pelec}, \mathbf{Prated}, \mathbf{Pmax}) \quad (6)$$

otherwise

2.3. Tip Speed Ratio and Rotor Speed

The tip speed ratio (TSR) of a wind turbine is defined as:

$$\lambda = \frac{\omega R}{v} \quad (7)$$

Where:

- ω is the rotor shaft mechanical speed of the wind turbine (rad/s)
- R is the Radius of the blade (m(
- v is the Air velocity (m/s)

2.4. Dynamic Torque-Speed Analysis

The torque generated by the turbine is given by:

$$T = \frac{P_{mech}}{\omega} \quad (8)$$

The torque-speed behavior was plotted using Torque Speed Curve to evaluate how the turbine behaves under different loading conditions.

III. RESULTS AND DISCUSSION

A MATLAB model was developed to simulate the aerodynamics of the 300-W horizontal-axis wind turbine (ATO-WT-S300) under specific wind speed and pitch angle conditions. The model illustrates power generation and provides important data on rotor torque and tip-speed ratio for evaluating turbine performance in different operation conditions.

The following sections present simulation results and the system's response to wind conditions and control parameters.

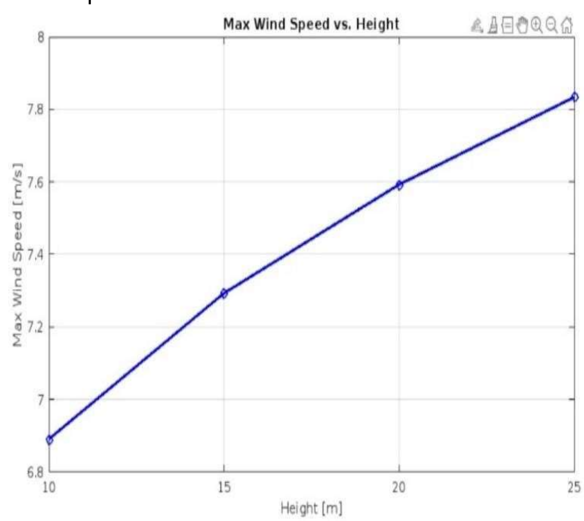

Fig. 5 Maximum Wind Speed as a Function of Height.

Figure 5 shows how wind speed increases with height above ground level, from 10 m to 25 m. At 10 m, the wind speed is around 6.88 m/s, while at 25 m, it reaches approximately 7.84 m/s. This increasing behaviour is expected, as wind faces less friction and surface roughness at higher altitudes (Stull, 1988).

This pattern follows the typical logarithmic wind profile found in the lower atmosphere (Stull, 1988). For wind energy systems, this relationship is important because placing wind turbines at higher elevations allows them to capture stronger and more consistent wind, improving energy output (Manwell, McGowan, & Rogers, 2009). Therefore, optimizing the height of wind turbine hubs is a key consideration in turbine design and site planning (Burton, Sharpe, Jenkins, & Bossanyi, 2011).

Choosing the right height for a wind turbine is important because wind speeds are higher and more stable at higher altitudes. Since power output depends heavily on wind speed, even a small increase in height can lead to a big boost in energy (Manwell et al., 2009). But taller turbines also cost more to build and maintain, so it's all about finding a balance between going high enough to get good wind, but not so high that it's not worth the extra cost. That's why optimizing the hub height is a key part of designing and planning wind turbines (Burton et al., 2011).

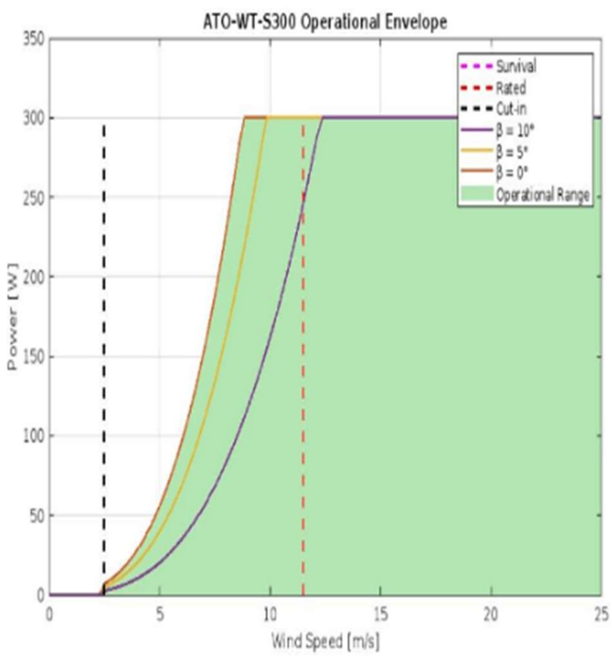

Fig. 6 Operating Envelope of the Wind Turbine.

Figure 6 shows the performance envelope shows that the wind turbine begins operating at a cut-in wind speed of 3 m/s and reaches rated power at 11 m/s. The turbine can safely operate up to a survival speed of 22m/s (Manwell et al., 2009). Within this range, the most effective performance occurs at β=0. Pitch control allows the turbine to adjust power output to match wind conditions and prevent mechanical stress under extreme conditions (Burton et al., 2011; Hansen, 2015)

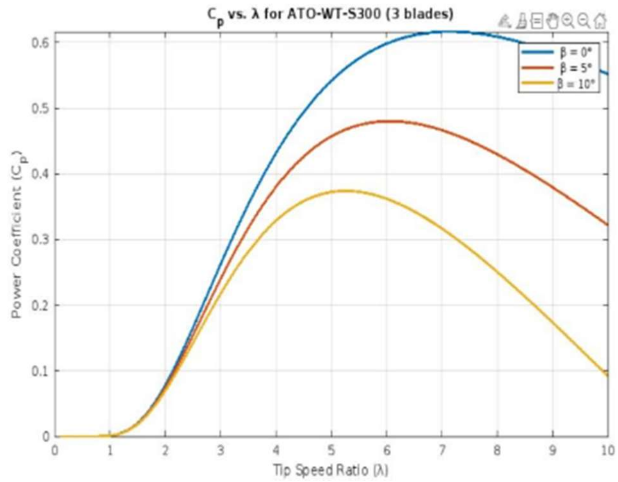

Fig. 7 Power Coefficient (Cp) vs. Tip Speed Ratio (λ).

Figure 7 shows the power coefficient Cp represents the efficiency of the wind turbine in converting wind energy into mechanical energy. The graph shows that the highest efficiency is achieved at a blade pitch angle of β=0, where Cp reaches approximately 0.61. This value approaches the theoretical Betz limit, indicating optimal aerodynamic performance (Manwell, McGowan, & Rogers, 2009; Burton, Sharpe, Jenkins, & Bossanyi, 2011).

As the pitch angle increases to 5° and 10°, the maximum Cp decreases and the peak of the curve shifts to a lower tip speed ratio. This demonstrates that increasing the pitch angle reduces aerodynamic efficiency (Hansen, 2015; Manwell et al., 2009).

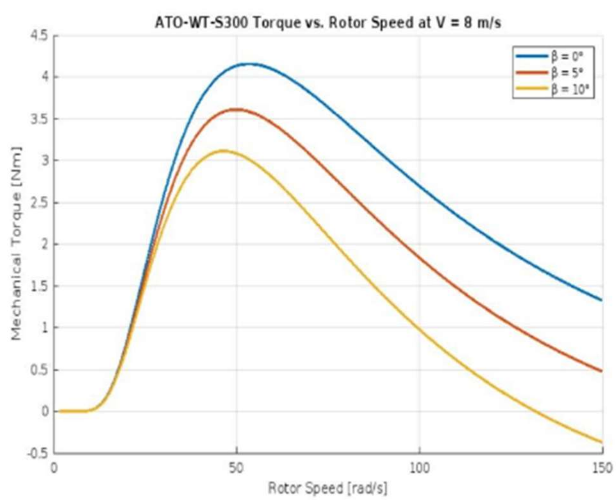

Fig. 8 Mechanical Torque Characteristics of the ATO-WT-S300 at V = 8 m/s.

Figure 8 shows how the mechanical torque of the ATO-WT-S300 wind turbine changes with rotor speed when the wind speed is fixed at 8 m/s. The graph compares three different blade pitch angles: 0°, 5°, and 10°. The curve for 0° pitch shows the highest torque, reaching over 4 Nm at around 50 rad/s. As the pitch angle increases to 5° and 10°, the maximum torque becomes smaller and happens at lower speeds (Hansen, 2015).

Each curve here is important because it shows how pitch angle affects turbine performance. A small pitch angle (like 0°) lets the blades capture more wind energy, which creates more torque. When the angle increases, the blades catch less wind, reducing the torque but this can also protect the turbine in strong winds (Hansen, 2015).

This helps to understand how to adjust the pitch angle to get the best performance or to prevent damage, making it useful for turbine control systems and design improvements (Manwell et al., 2009).

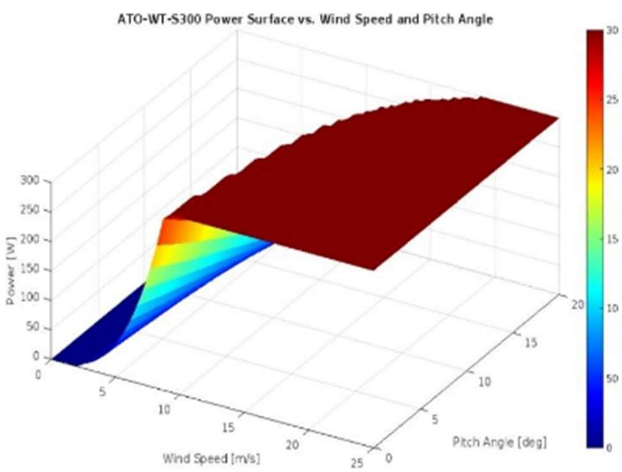

Fig. 9 Power Output vs. Wind Speed and Blade Pitch Angle.

Figure 9 shows the three-dimensional surface plot illustrates the variation in power output with changing wind speed and blade pitch angle. The turbine reaches its rated power of 300 W at approximately 11 m/s wind speed when the pitch angle is zero (Manwell et al., 2009). At higher pitch angles, the power output decreases across all wind speeds.

This trend confirms that a lower pitch angle allows the turbine to extract more energy from the wind, while higher pitch angles are used to limit power during high wind speeds for safety and load control (Hansen, 2015; Burton et al., 2011).

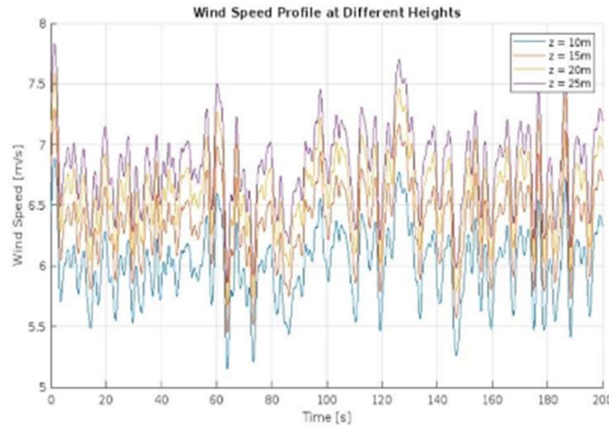

Fig. 10 Wind Speed Time Series at Multiple Elevation.

Figure 10 shows how wind speed changes over time at different heights (10 m, 15 m, 20 m, and 25 m) during a 200-second period. From the graph, we can see that wind speed is generally higher at greater elevations

(Arya, 2001). For example, the speed at 25 m often goes above 7 m/s, while at 10 m it usually stays below 6.5 m/s.

The shape of each curve is important because it shows not only how wind behaves differently at each height, but also how wind speed changes constantly over time (Arya, 2001).

Higher wind speeds mean more power, but the constant fluctuations (turbulence) can affect how the turbine blades and control systems respond (Burton et al., 2011).

This helps to build more efficient and stable wind turbines and helps in choosing the best height for installation (Burton et al., 2011).

IV. CFD SIMULATION RESULTS AND ANALYSIS

As part of the aerodynamic evaluation of the horizontal-axis wind turbine (HAWT), Computational Fluid Dynamics (CFD) simulations were conducted using ANSYS 2023 R1. The focus of the analysis was to investigate the pressure and velocity distribution around the rotor blades under steady wind conditions. The results are presented in the following figures and interpreted below. to analyze the turbine's performance (ANSYS Inc., 2023).

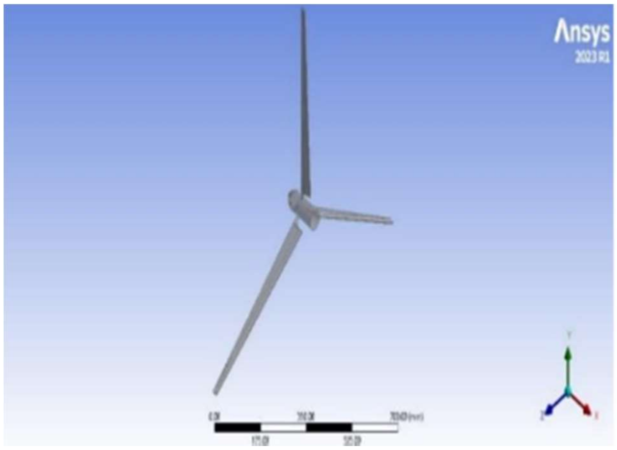

Fig. 11 3D Model of Wind Turbine Rotor.

This is the 3D model of a horizontal-axis wind turbine (HAWT) created in ANSYS 2023 R1. It shows a three-blade rotor connected to the hub, which is a common setup in modern wind turbines (Hansen, 2015; Burton, Sharpe, Jenkins, & Bossanyi, 2011). The size scale below helps understand the blade dimensions, going up to 700 mm. This model was used for CFD simulations to see how air flows around the blades and to analyze the turbine's performance (ANSYS Inc., 2023).

1. Results at Zero Blade Pitch

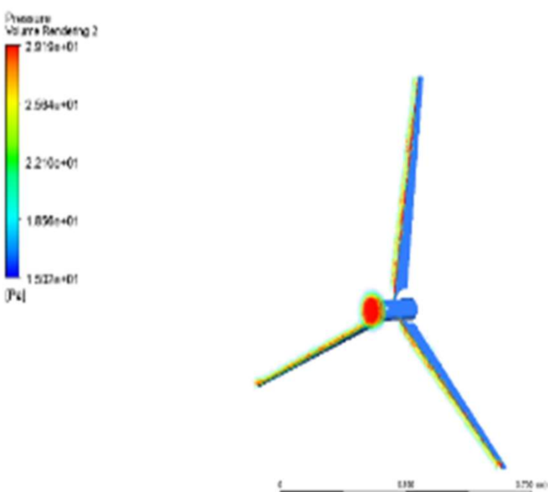

Fig. 12 Volume Rendering of Pressure Field.

Figure 12 shows the three-dimensional pressure distribution around the wind turbine. The pressure ranges from 15.02 Pa to 29.19 Pa, with the highest values concentrated near the hub of the rotor. This is due to the stagnation of flow at the blade roots, where incoming wind directly interacts with the central region of the turbine (Manwell, McGowan, & Rogers, 2009).

The pressure decreases outward along the blade span, demonstrating how the aerodynamic shape of the blades facilitates airflow acceleration and pressure drop, which in turn contributes to lift (Hansen, 2015). This global view of the pressure field helps illustrate the overall aerodynamic environment in which the turbine operates. While not detailed on the blade surface, this volume rendering is effective for providing a macro-level understanding of flow behavior (Burton et al., 2011).

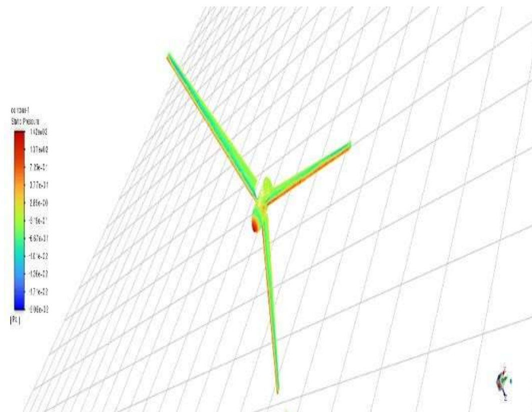

Fig. 13 Static Pressure Contour Plot.

Figure 13 presents a 2D static pressure contour plot taken through a vertical plane intersecting the turbine rotor. This visualization offers a more precise and technical view of how pressure varies across and behind the blade surfaces. The pressure ranges from approximately -20.6 Pa to 142 Pa, showing a strong differential between the pressure and suction sides of the blades (Hansen, 2015).

This pressure difference is the driving force behind an aerodynamic lift, which causes the rotor to spin. The downstream region, where pressure drops significantly, represents the wake zone, where kinetic energy has been extracted from the airflow (Manwell et al., 2009). These pressure contours are essential for evaluating blade loading, structural forces, and aerodynamic efficiency (ANSYS Inc., 2023).

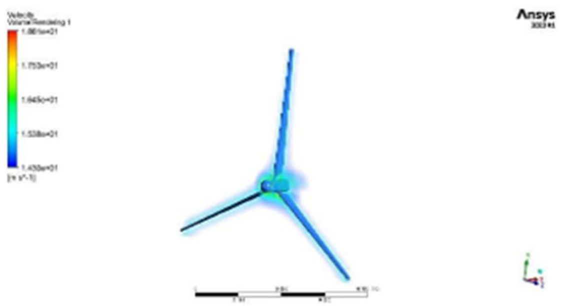

Fig. 14 Volume Rendering of Velocity Field.

Figure 14 shows the velocity distribution around the turbine, with values ranging from 14.30 m/s to 18.61 m/s. Higher velocities are observed near the blade tips, where rotational speed and aerodynamic effects are greater (Burton et al., 2011). The velocity drop behind the rotor indicates that the wind has lost kinetic energy to the turbine, confirming successful energy extraction.

The wake region directly downstream of the rotor is a key indicator of performance. The contrast between the fast-moving flow around the rotor and the slower wake flow is consistent with Betz's Law, which limits the theoretical maximum efficiency of a wind turbine to 59.3% (Manwell et al., 2009). This visualization helps confirm that the turbine design effectively captures wind energy and produces a realistic aerodynamic response (Hansen, 2015).

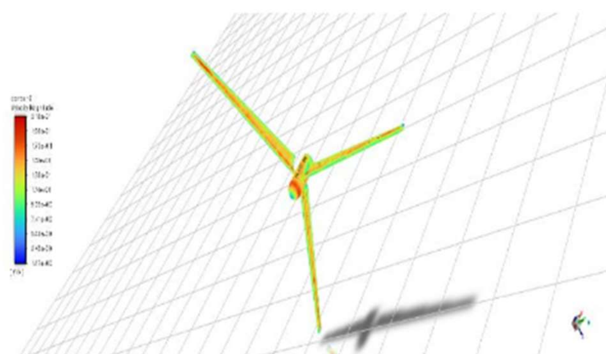

Fig. 15 Velocity Magnitude Contours Around the Wind Turbine.

Figure 15 illustrates the velocity distribution around the wind turbine, with values ranging from 1.47 m/s to 21.3 m/s. The highest velocities are seen near the blade tips, where the rotational speed is greatest, while the lowest velocities appear in the wake region behind the rotor (Burton et al., 2011).

The wake forms due to the extraction of energy from the wind, resulting in slower airflow downstream. This effect is important when designing wind farms, as turbines placed directly behind others will operate in lower-speed, more turbulent air, reducing their efficiency (Manwell et al., 2009).

This simulation helps visualize the flow behavior and energy conversion process and highlights how CFD tools can be used effectively in wind turbine analysis and layout planning (ANSYS Inc., 2023).

2. Comparison of Velocity Contours at Different Blade Pitch Angles (0°, 10°, 15°)

In this project, CFD simulations were carried out to studythe effect of varying blade pitch angles on the aerodynamic performance of a horizontal-axis wind turbine (HAWT). The blade pitch angle is a critical parameter that determines how much wind energy is captured by the turbine (Hansen, 2015; Manwell, McGowan, & Rogers, 2009). Three cases were analyzed, with pitch angles set to 0°, 10°, and 15°, and the results were compared using velocity magnitude contours around the turbine (ANSYS Inc., 2023).

At 0° pitch angle, the blades are aligned perpendicular to the wind direction, which means they have little to no tilt. In this setup, the airflow around the blades is relatively low in speed, especially near the root of the blade. The wake region behind the turbine appears.

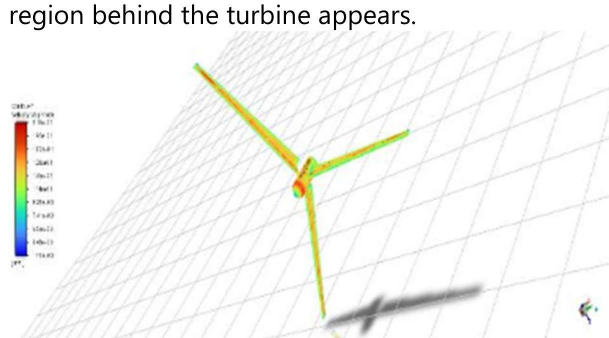

Fig. 16 Velocity Magnitude Contours of $\beta=0^0$.

When the pitch angle is increased to 10°, a significant improvement in performance is observed. The velocity near the blade tips increases, as shown by the stronger red regions in the contour plot. The wake becomes narrower and more focused, indicating more efficient energy extraction. This setup provides a better angle of attack, which increases lift and reduces drag, making it one of the most effective angles for regular turbine operation under normal wind conditions (Hansen, 2015).

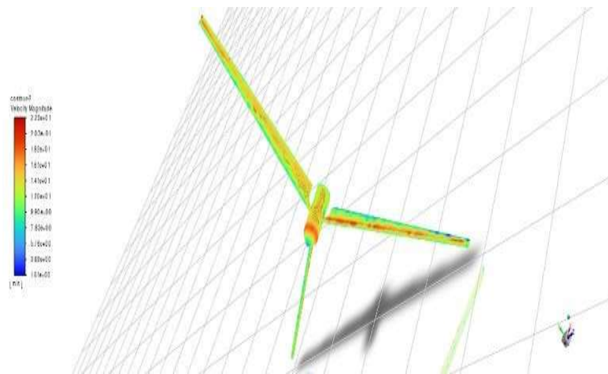

Fig. 16 Velocity Magnitude Contours of $\beta=10^0$.

At 15° pitch angle, the blades are tilted even more aggressively. While high-speed airflow is still visible around the blade tips, the flow patterns start to show signs of disturbance, especially near the trailing edge. This can indicate the onset of flow separation or aerodynamic stall, which reduces the efficiency of the turbine (Manwell et al., 2009). In real-world applications, such a pitch angle might be used during high wind speeds or as part of a control strategy to reduce power output and protect the turbine (Burton et al., 2011).
Overall, increasing the pitch angle initially improves performance (from 0° to 10°), but excessive tilting (15°) may lead to reduced efficiency due to adverse flow effects (Hansen, 2015).

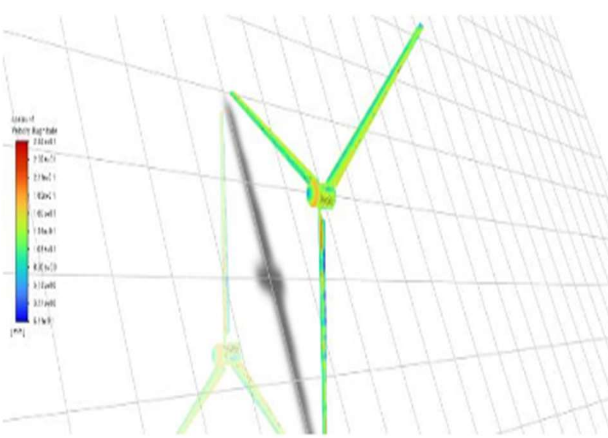

Fig. 17: Velocity Magnitude Contours of $\beta=15^0$.

VIII. CONCLUSION

The study on the modeling, simulation, and aerodynamic analysis of a small-scale Horizontal Axis Wind Turbine (HAWT) provides valuable information about the performance and optimization of wind energy systems. By combining MATLAB simulations and Computational Fluid Dynamics (CFD) using Ansys, the research highlights the most important factors affecting turbine efficiency, including wind speed, blade pitch angle, and rotor dynamics. The results illustrate the importance of these parameters to maximize energy capture while ensuring structural integrity and safe operation.

IX. KEY OUTCOMES OF THE STUDY INCLUDE

Optimal Pitch Angle: The simulations demonstrate that a blade pitch angle of 0^0 produces the highest power coefficient Cp, approaching the theoretical Betz limit. Increasing the pitch angle to 10^0 or 15^0 reduces aerodynamic efficiency but may be necessary for load control during high wind speeds.

Wind Speed and Height: The logarithmic wind profile shows that there is a correlation between higher hub heights and increased wind speeds, emphasizing the importance of optimal turbine placement to enhance energy output.

Torque and Power Characteristics: The torquespeed analysis shows that lower pitch angles generate higher mechanical torque, while the power output reaches its rated capacity at a wind speed of 11 m/s. The turbine’s operation was clearly defined, with cutin, rated, and cut-out wind speeds to ensure safe and efficient performance.

CFD Insights: The CFD simulations provide neat visualizations of pressure and velocity distributions around the rotor blades, verifying the aerodynamic behavior predicted by theoretical models. The wake effects and flow separation observed at higher pitch angles provide critical data for blade design optimization and control strategies.

The study also investigates the HAWT within the wide field of wind energy technology, comparing it to Vertical Axis Wind Turbines (VAWTs) and highlighting HAWTs' superior efficiency and scalability. The advancements in blade materials, adaptive control systems, and hybrid energy solutions further strengthen the role of HAWTs in sustainable energy systems.

X. FUTURE DIRECTIONS

To build on this research, future work could explore:

- Advanced materials and flexible blade designs to reduce mechanical stress and extend turbine lifespan.
- Integration of machine learning for real-time performance optimization as well as predictive maintenance.
- Large-scale wind farm simulations to study wake interactions and overall efficiency.
- Offshore applications, utilizing reliable wind resources and addressing the engineering challenges that would show up in these applications.

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