Article

Optimizing Performance and Design Simulation of a 100 KW Single Rotor Horizontal Axis Wind Turbine

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ABSTRACT: As wind energy becomes increasingly vital in global energy strategies, optimizing wind turbine design is essential. This research focuses on the development of a 100 kW single rotor horizontal axis wind turbine (HAWT) tailored to meet the energy needs of Jamshoro, Pakistan. The turbine design leverages SolidWorks for structural modeling and is validated through comprehensive simulations using ANSYS and Q-Blade. Operating at an optimal wind speed of 6.9 m/s, the turbine achieves maximum efficiency, as indicated by the highest power factor. This efficiency translates to an estimated power output of approximately 100 kW, suitable for common household consumption. The study integrates regional climatic data and wind conditions to enhance turbine performance and durability. The findings offer a sustainable energy solution for Jamshoro, contributing to Pakistan's renewable energy infrastructure and addressing local energy demands effectively. The focus of this study will be Jamshoro, a region in Pakistan as a case study. The software simulations will consider a variety of elements, including as wind speeds, variable loads, and environmental factors unique to the chosen region (Jamshoro). This research proposes a sustainable solution for addressing the energy demands in Jamshoro by integrating accurate data based on software analysis with real-world concerns, adding to the larger goal of developing sustainable sources of energy in Pakistan.

Keywords: Horizontal axis wind turbine (HWAT); Renewable energy; Wind turbine design; Software analysis

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1. Introduction

The history of wind energy can be traced back several thousand years; it means that people started to use wind energy much earlier than the Industrial Revolution. Historically, windmills have been applied since the early ages of Egypt and China to perform tasks like water lifting and grain grinding. It is classified as a renewable energy source because the wind is a natural element that is freely available and can be easily replenished through heat. Whereas coal, oil, and natural gas are finite, wind energy is renewable, eco-friendly, and does not lead to emissions of greenhouse gases and climate change [1]. Wind power, also known as the conversion of the kinetic energy of the wind into electrical power via wind turbines, is a sustainable energy source compared to conventional power derived from burning fossil fuels.

It also plays a role in energy self-reliance since it is a form of energy that is produced locally, which helps reduce energy imports [2]. This enhances energy security for countries and reduces the vulnerability of energy market fluctuations globally. Wind energy should be integrated into the energy portfolio to increase a country's energy security and reduce dependence on imported energy resources. Also, wind energy has been relatively cheap in the last few years and can be deemed a potential source of electricity generation. Technological improvements and increase in the size of the wind turbines have reduced the cost of wind energy, which has reduced the cost of energy to the consumers and firms [3].

Pakistan has problems in advancing its domestic energy resources, such as wind energy, due to energy scarcity, lack of policy support, difficulties in investment, and technological constraints. The country has largely depended on

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fossils and hydropower, resulting in energy shortages and not paying much attention to renewable energy sources [4]. Constraints such as policy, institutional, regulatory, fiscal, and technical constraints limit the development of a strong renewable energy industry. Insufficient technical information and data on local conditions and resources hamper the accurate evaluation of wind energy potential in Pakistan. To overcome these challenges, policy support, investment incentives, and better data collection are vital for Pakistan to tap its indigenous energy resources, such as wind power, for sustainable development [5].

HAWTs are commonly used in large-scale wind farms because of their efficiency and power generation abilities. The structure of the HAWT blades is one of the key considerations that affect its performance. Parameters like blade length, airfoil shape and twist distribution greatly influence the ability to harness wind energy. Also, the wind speed at the turbine's location directly affects the power it produces [6]. Wind speed is directly proportional to the energy produced; low wind speeds may negatively affect the system's efficiency. The height at which the turbine is installed also affects its ability to face higher wind speeds and better airflow. Taller turbines can capture more powerful and stable winds since they are higher up, enhancing efficiency. Maintenance and reliability are crucial to the proper functioning of HAWTs. Some factors that affect the turbine's efficiency include gearbox condition, blade condition, and general system condition. Other factors influencing HAWT performance include environmental factors such as turbulence, wind shear, and site-specific factors. Selection and evaluation of the site are significant factors that contribute to HAWTs' energy production efficiency [7].

Wind energy is popularly referred to as a clean energy because it has less or no harm to the environment and is renewable [8]. Wind power is a renewable energy source that produces electricity without emitting greenhouse gases or other pollutants that affect the climate and the air. Wind power is one of the most effective means of producing electricity that does not pollute the environment and deplete the natural resources since the fossil fuels are non-renewable sources of energy that worsen the global climate. The environmental friendliness of wind energy can be characterized by the following features: clean electricity generation, lower emissions, low water consumption, efficient land use, and energy self-sufficiency [9]. Wind energy is important in mitigating greenhouse gas emissions, fighting climate change, and creating a healthier environment for the current and future generations.

2. Methods

This section has been categorized into following sub-sections.

2.1. Design and Simulation Process

The design of the 100 kW single rotor horizontal axis wind turbine (HAWT) was conducted using SolidWorks. The turbine's parameters were meticulously verified through comprehensive simulations using advanced software tools including ANSYS and Q-Blade. These tools allowed for detailed analysis of aerodynamic performance, structural integrity, and overall efficiency under various operational conditions.

The design process involved:

- **Initial Design in Solid Works**: Creating a detailed 3D model of the wind turbine, including the rotor, blades, and tower.
- **Aerodynamic Analysis**: Using Q-Blade to simulate the aerodynamic performance of the turbine, focusing on optimizing the blade shape and pitch to maximize lift and minimize drag.
- **Structural Analysis**: Conducting structural simulations in ANSYS to ensure the turbine can withstand mechanical stresses and environmental conditions over its 30-year design life.
- **Performance Optimization**: Iteratively refining the design to achieve optimal performance at the design wind speed of 6.9 m/s, which was determined to provide the highest power factor and efficient energy conversion.

2.2. Climatic Conditions and Wind Potential

The case study focuses on Jamshoro, a region in Pakistan known for its significant wind energy potential. To ensure the design is tailored to the specific conditions of Jamshoro, extensive climatic data and wind resource assessments were conducted.

- **Temperature Range**: The region experiences temperatures ranging from −20 °C to 55 °C. These conditions were factored into the design, particularly in the selection of materials and cooling systems to ensure reliable operation.

- **Extreme Weather Events**: The turbine is designed to withstand extreme wind speeds up to 24 m/s (86.4 km/h), ensuring durability and safety during adverse weather conditions.
- **Average Wind Speed**: Based on data from local meteorological stations, the average wind speed in Jamshoro is approximately 6.9 m/s [10].
- **Wind Speed Variability**: Seasonal and diurnal variations in wind speed were analyzed to predict energy production patterns and ensure consistent power generation.
- **Wind Direction**: Predominant wind directions were identified to optimize the yaw system and ensure the rotor faces the wind for maximum efficiency.

2.3. Case Study Justification

Jamshoro was selected for this study due to its favourable wind conditions and the need for sustainable energy solutions in the region. By integrating accurate climatic data with advanced simulation tools, this research aims to propose a viable wind energy solution tailored to local needs, contributing to the broader goal of enhancing renewable energy infrastructure in Pakistan.

3. Design Parameters

The significant design parameters in the proposed HAWT are blade length, blade pitch, rotor diameter, tower height, generator type, control system and environmental impact. The control system monitors and adjusts the turbine's operation to optimize power output and protect the turbine from damage due to extreme weather conditions. The location of the turbine, wind speed, turbulence, and other environmental factors all play a role in the design of a HAWT. The maximum operating temperature has been increased to 55 °C. This enhancement involves several key modifications: using higher temperature-rated components such as a generator with class H insulation and a Siemens PLC designed for higher temperature operation; implementing advanced cooling systems to manage internal temperatures effectively; and selecting materials and coatings that maintain integrity and protect against thermal degradation at elevated temperatures. These improvements ensure the wind turbine's reliability and performance in hotter climates, thereby enhancing its operational durability and efficiency over its 30-year design life. The turbine must be designed to withstand the expected environmental conditions and operate reliably over a long period. The specification of each design parameter is provided in Table 1. If the temperature exceeds the specified range of −20 °C to 55 °C, the wind turbine incorporates several safety and performance mechanisms to manage these conditions and protect its components. An automated control system will shut down the turbine to prevent damage when temperatures surpass safe operational limits. High-precision temperature sensors continuously monitor critical components, triggering preemptive actions like load reduction or shutdown if necessary. Advanced cooling systems help maintain safe operational temperatures during temporary spikes, while materials and design choices, such as class H insulation, ensure durability under extreme conditions. If temperatures exceed 55 °C, the turbine will halt operation to avoid overheating, and at temperatures below −20 °C, it may shut down to prevent issues like material brittleness or ice formation. These measures ensure the turbine's protection and reliable performance across a wide range of environmental conditions.

Table 1. Specifications of design parameters.

	Characteristics	Specifications
Main data	Design life	30 years
	Rated power	100 kW
	Rated wind speed	11 m/s
	Cut-in | Cut-out wind speed	2.75 m/s (9.9 km/h) (6 mph) | 20 m/s(72 km/h) (45 mph)
	Extreme wind speed	70 m/s (252 km/h) (157 mph)
	Operating temperature	−20 ℃ to 55 ℃
Rotor	Rotor diameter	50 m (164 ft)
	Swept area	1962 m^2 (21,118 ft^2)
	Rotor speed	Variable, up to 57 rpm
Generator	Type	PM Generator
	Model	3-phase
	Generator	100 kW, 400 V, 42.4 Hz, 1.25 service factor
	Drivetrain	Direct drive (no gearbox)
	Generator enclosure and insulation	Totally enclosed, weather-proof, class F insulation, IP55, maintenance-free
Control system	Controller model	Siemens PLC
	Advanced features	Data logging and direct integration with safety system
	Control strategy	Maintenance free active stall-regulated
	Weather sensors	Wind speed, wind direction, temperature
Yaw system	Type	Electric auto-yaw
Material	Steel components	High quality, as per ASTM standard
	Corrosion protection	Hot-dip galvanized or zinc-coated, as per ASTM standards
Blade	Design	Fixed-pitch (no moving parts)
	Length	10 m (33 ft)
Tower	Tower-hub height	30 m free-standing and tilt up

4. Theoretical Calculations

This section has been categorized into following sub-sections.

4.1. Maximum Power Co-Efficient

The maximum power coefficient of a wind turbine refers to the maximum amount of power that the turbine can extract from the wind. It is typically denoted by the symbol Cp. The maximum power coefficient of a wind turbine is determined by a number of factors, including the design of the blades, the size of the turbine, and the wind speed. Generally, the maximum power coefficient of a wind turbine is around 0.59, which is known as the Betz limit. This theoretical limit is based on the idea that the turbine can extract no more than 59.3% of the energy in the wind [11]. In practice, however, wind turbines typically achieve a maximum power coefficient that is lower than the Betz limit, due to factors such as the inefficiency of the blades at high wind speeds and the effects of turbulence. According to the formula:

$$\mathrm{Cp} \propto \frac{1}{v^3} \tag{1}$$

The maximum power co-efficient is inversely proportional to the cube of wind speed and also inversely proportional to maximum power output.

$$\mathrm{P} = \frac{1}{2}\rho \mathrm{A} \mathrm{v}^3 \mathrm{Cp} \tag{2}$$

where P is power output, ρ represents density of air, V is wind speed, A depicts swept area, and Cp is maximum power co-efficient. By using Equation (1) and Equation (2), several calculations are made as given below in Table 2.

Table 2. Operational performance data of the wind turbine for varying wind speeds.

Wind Speed (m/s)	Cp	Tip Speed Ratio (λ)	Power Output (kW)	Torque Co-Efficient (CT)	Torque Developed (TT) (Nm)
6	0.38	24.87	99.04	0.015	664.20
6.5	0.30	22.95	125.9	0.013	666.69
6.9	0.25	21.63	150.6	0.012	664.58
7.5	0.19	19.90	193.4	0.010	648.6
8	0.16	18.65	234.7	0.009	662.91

4.2. Wind Power Vs. Wind Speed

The power output of a wind turbine is directly proportional to the cube of the wind speed. This is known as the wind power law, which can be expressed mathematically as:

$$P \propto v^3 \tag{3}$$

where P is the power output of the wind turbine and v is the wind speed.

This means that a small increase in wind speed can lead to a significant increase in the power output of a wind turbine. For example, if the wind speed doubles, the power output of the wind turbine will increase by a factor of eight as shown in Table 2. However, it's important to note that the wind power law assumes that the wind is uniform and undisturbed, which is not always the case in real-world conditions. Turbulence, wind shear, and other factors can all affect the performance of a wind turbine and can lead to deviations from the predicted power output.

4.3. Effect of Wind Speed on Blade Design

The wind speed affects the aerodynamic forces acting on the wind turbine blades. As the wind speed increases, the blades must be designed to withstand the increased forces acting on them. This requires the blades to be longer, stronger, and more rigid. The shape of the blade may also be modified to optimize the aerodynamic performance at high wind speeds, which can involve changes to the airfoil shape, blade twist, and blade chord length [12]. Figure 1 represents the Blade profile design.

Figure 1. Blade profile design (NACA 4412) of HAWT.

4.4. Effect of Wind Direction on Blade Design

Wind direction also has an impact on the blade design. Wind turbines are typically designed to operate optimally when the wind is coming from a specific direction. This is known as the "yaw angle" or "azimuth angle" of the wind turbine. The blade design may be optimized to capture the maximum amount of energy from the wind when it is coming from this specific direction. This can involve changes to the blade shape, twist, and chord length, as well as the use of technologies such as blade pitch control and rotor yaw control to adjust the blade angle and orientation relative to the wind direction [13–16].

A blade's performance is directly impacted by wind speed. Higher aerodynamically efficient blades can often extract more energy or produce more thrust at higher wind speeds. The blades' profile, shape, and angle of attack are all optimized for the targeted wind speed range in order to deliver the optimum performance. Designers frequently take lift, drag, and stall characteristics into account to provide the best possible energy conversion or propelling efficiency.

5. Results and Discussion

Analysis of the structural integrity and performance of wind turbine blades must take into account the shear stress on the blades' surface.

The force per unit area operating parallel to an object's surface is referred to as shear stress. When referring to wind turbine blades, it refers to the force that the wind exerts on the blade surface, which results in shear deformation. Wind speed, air density, blade shape, and the turbine's rotational speed all affect how much shear stress is placed on wind turbine blades. Shear stress may rise as a result of stronger winds and denser air. The distribution of shear stress over the blade surface is also influenced by the design and form of the blade, including its length, chord length, twist, and airfoil profile. The tangential force per unit area applied to a surface is known as shear stress. It is the force resulting from the wind passing over the blade surface in the context of wind turbine blades. When building wind turbine blades, shear stress is a crucial component to take into account because it can cause the blade to bend or deform as shown in Figure 2.

Researchers often utilize computational fluid dynamics (CFD) models or experimental testing to evaluate the shear stress on wind turbine blades. These techniques aid in forecasting the flow behaviour at the blade surface and computing the shear forces that follow. Researchers may optimize the blade design and make sure that the material selected can sustain the anticipated pressures for the duration of the turbine's operating lifetime by analyzing the shear stress distribution.

Utilizing computational fluid dynamics (CFD) software, velocity paths in a wind turbine may be simulated. Hence, the fluid flow including the movement of air around a wind turbine is examined in the current research. To perform the flow simulation, a 3D model of the wind turbine's geometry is created using the CFD program. The wind turbine shape can be discretized into tiny parts or cells using a computational mesh. The mesh resolution needs to be both computationally efficient and fine enough to capture flow details. The inlet and outlet borders for the flow simulation in the boundary conditions section are set. While the flow enters the domain at the inlet boundary, it leaves the domain at the outlet boundary. Determining boundary conditions for the turbine surfaces, such as the no-slip requirement for the rotor blades, may also be necessary. In the next step, a turbulence model is picked that can correctly depict the turbulent behaviour of the flow. The k-model, or Reynolds-averaged Navier-Stokes (RANS) equations are examples of common turbulence models. In the last step, the solver settings are configured, which include the time step size, the convergence criterion, and any other elements unique to the CFD programme. Once it has reached a steady-state or has captured the desired flow behaviour, let the simulation continue. The simulation determines the flow velocity at various points within and outside of the wind turbine. Figure 3 represents the flow simulation to show velocity trajectories.

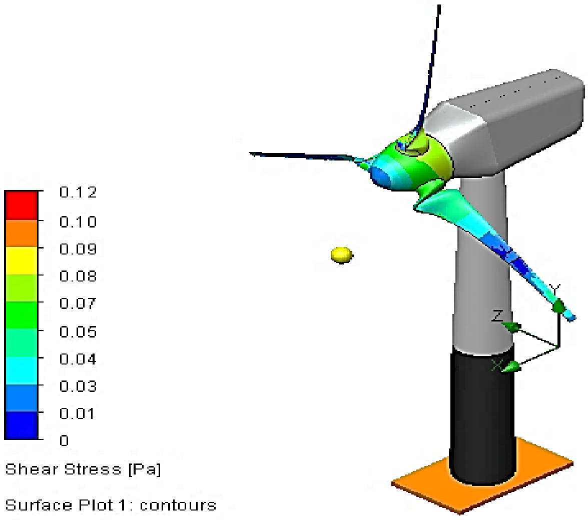


Figure 2. Evaluating the shear stress on the surface of blades.

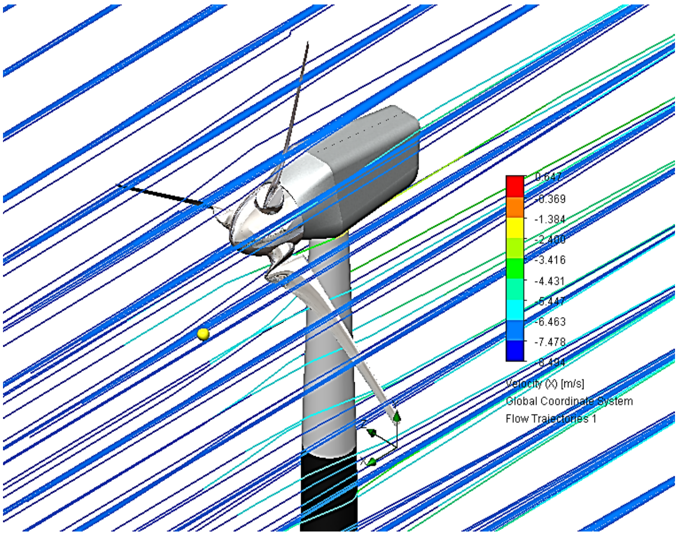


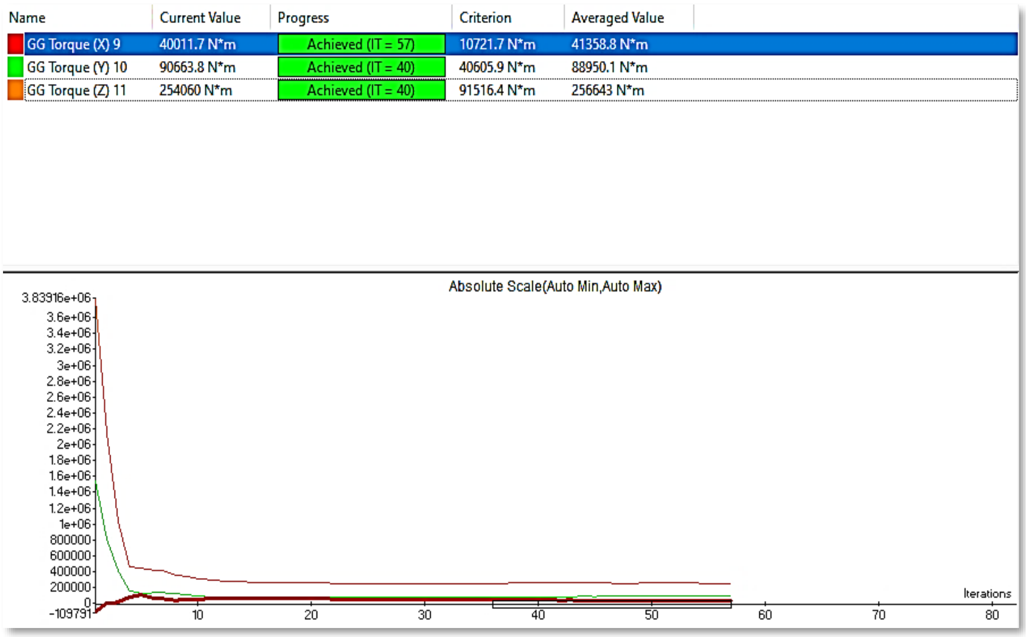
Figure 3. Flow simulation to show the velocity trajectories.

Figure 3 is an illustration of the airflow surrounding a wind turbine. Colors probably represent speed, with blue being the slowest and red being the fastest. Trajectories, or the direction and path taken by the air, are indicated by arrows or lines. At certain sites, wind speed may be represented by numbers.

The simulation results are evaluated using the CFD software’s post-processing features. The flow routes and velocity trajectories are often visualized using streamlines or particle tracking methods. A wind turbine known as a horizontal-axis wind turbine (HAWT) has its primary rotor shaft horizontally and parallel to the ground. HAWTs are frequently used to capture wind energy and transform it into electricity. Understanding the performance and effectiveness of HAWTs requires careful consideration of torque calculations. The rotor blades of a HAWT are fastened to a central hub, which rotates the rotor along its axis in response to wind. Three directions—X, Y, and Z—can be used to analyze the torque produced by the wind turbine.

The torque simulation results along the X, Y, and Z directions are displayed in the Figure 4. Through a number of iterations, it seems to be tracking torque (maybe for convergence). There is an average value and a target value (Criterion) for each direction (X, Y, and Z). The horizontal axis of the turbine rotor is normally aligned with the X-direction. The driving torque, sometimes referred to as the torque along the X-axis, is what causes the turbine rotor to rotate. It is produced by the aerodynamic forces that the wind exerts on the rotor blades. The size of the X-direction torque is affected by variables including wind speed, blade design, and blade angle of attack. The Y-direction is horizontal and perpendicular to the rotor axis. The term “yawing torque” is frequently used to describe the torque in the Y-direction. When the turbine is not exactly aligned with the direction of the wind, the force of the wind acting on the rotor blades causes it. The wind turbine’s yaw system, which modifies the rotor’s orientation, counteracts the yawing torque, which has a tendency to align the turbine with the wind. The Z-direction is vertical and parallel to both the X and Y axis. The tilting or pitching torque is the force acting in the Z-direction. It is caused by the wind’s pressure pushing on the rotor blades, which tends to tilt them upward or downward. A pitch control system typically counteracts the pitching torque by adjusting the angle of attack of the blades to improve performance and prevent undue strain on the turbine construction.

There is also a need to take into account the wind speed components along the X, Y, and Z directions when calculating velocity for a HAWT.

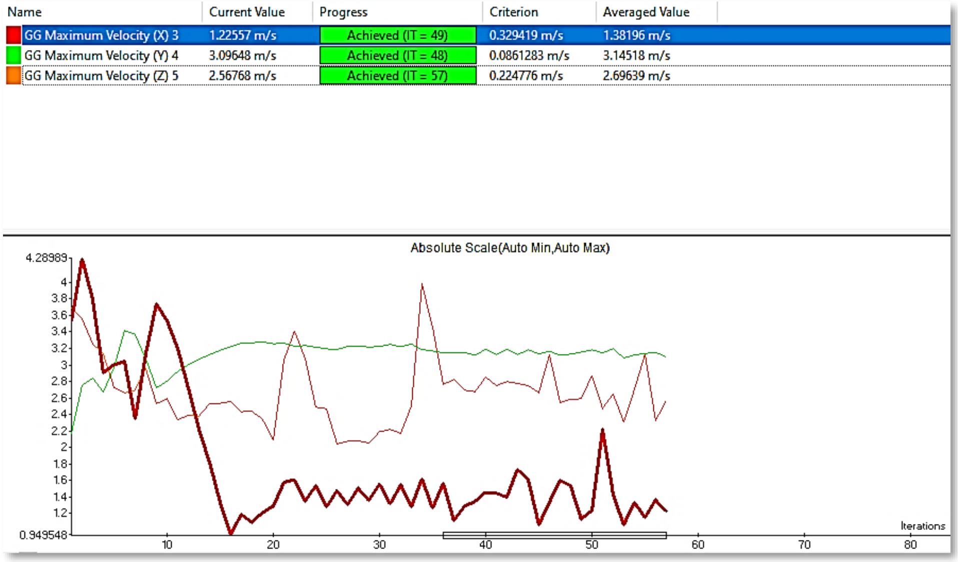


Name	Current Value	Progress	Criterion	Averaged Value
🟥 GG Torque (X) 9	40011.7 N*m	Achieved (IT = 57)	10721.7 N*m	41358.8 N*m
🟩 GG Torque (Y) 10	90663.8 N*m	Achieved (IT = 40)	40605.9 N*m	88950.1 N*m
🟧 GG Torque (Z) 11	254060 N*m	Achieved (IT = 40)	91516.4 N*m	256643 N*m

Figure 4. Torque calculation along X, Y and Z direction.

Figure 5 shows the maximum velocity achieved in X, Y, and Z directions during a simulation of HAWT. The wind turbine’s horizontal axis is represented by the X-direction. We are interested in the wind speed perpendicular to the rotor plane in this direction. An anemometer installed in front of the turbine can be used to measure the wind speed in the X-direction, or it can be predicted using weather information. The vertical axis is represented by the Y-direction. The vertical forces acting on the wind turbine blades may be calculated using the wind speed component in the Y-direction. The stability of the atmosphere, the amount of wind shear, and the height of the turbine above the ground can all have an impact on the Y-direction velocity. Along the rotor shaft, the Z-direction denotes the axial direction of a wind turbine. Calculating the rotor’s rotational speed and the wind turbine’s power output both depend on the wind speed component in the Z-direction. Anemometers installed on the turbine mast at various heights can be used to gauge or measure the wind speed in the Z-direction.

When a HAWT is subjected to different loads, such as wind forces, gravity, and mechanical stresses, the turbine’s blades may deform. The weights may result in the blades bending, twisting, or deforming in various ways. Figure 6 shows the deformation in the blade by applying load.



Name	Current Value	Progress	Criterion	Averaged Value
🟥 GG Maximum Velocity (X) 3	1.22557 m/s	Achieved (IT = 49)	0.329419 m/s	1.38196 m/s
🟩 GG Maximum Velocity (Y) 4	3.09648 m/s	Achieved (IT = 48)	0.0861283 m/s	3.14518 m/s
🟧 GG Maximum Velocity (Z) 5	2.56768 m/s	Achieved (IT = 57)	0.224776 m/s	2.69639 m/s

Figure 5. Velocity calculation along X, Y, Z direction.

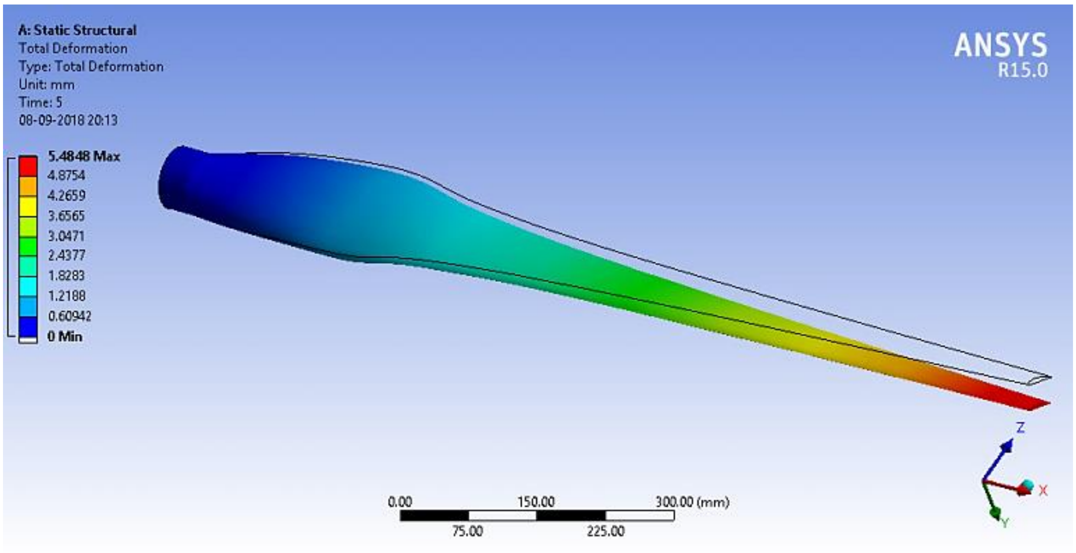


Figure 6. Deformation in the blade by applying load.

The aerodynamic forces exerted on the blades by the wind are the main cause of blade distortion. There is a pressure differential between the upper and bottom surfaces of the blades when the wind passes over their curved surfaces, producing lift and drag forces. These forces can cause deformation in the blades by producing bending moments and torsional stresses. The operating circumstances of the turbine, such as wind speed, turbulence, and yaw misalignment, can also have an impact on blade deformation. In addition, the blade's resistance to deformation may be impacted by elements including its design, manufacturing standards, and material qualities.

Modelling the aerodynamic forces and flow characteristics that the wind turbine blades encounter as they revolve is necessary to simulate the velocity vectors for the blades. For such simulations, a variety of techniques and software tools are available, such as computational fluid dynamics (CFD) and blade element momentum (BEM) theory.

A computational fluid dynamics (CFD) simulation for a wind turbine blade is visualized in the Figure 7. The airflow velocity around the blade is being computed using the simulation. Red is the color with the highest velocity, and blue is the color with the lowest velocity.

A popular CFD program for modelling fluid flow and heat transport processes is ANSYS Fluent. The simulation of wind turbines, it offers sophisticated modelling capabilities. An open-source CFD program with a sizable user base is called Open FOAM. It provides a variety of solutions and tools for modelling wind turbines. Open-source CFD software designed exclusively for wind turbine simulations is called FAST/Foam. To capture the impacts of both local and global flow, it blends the BEM method with CFD techniques.

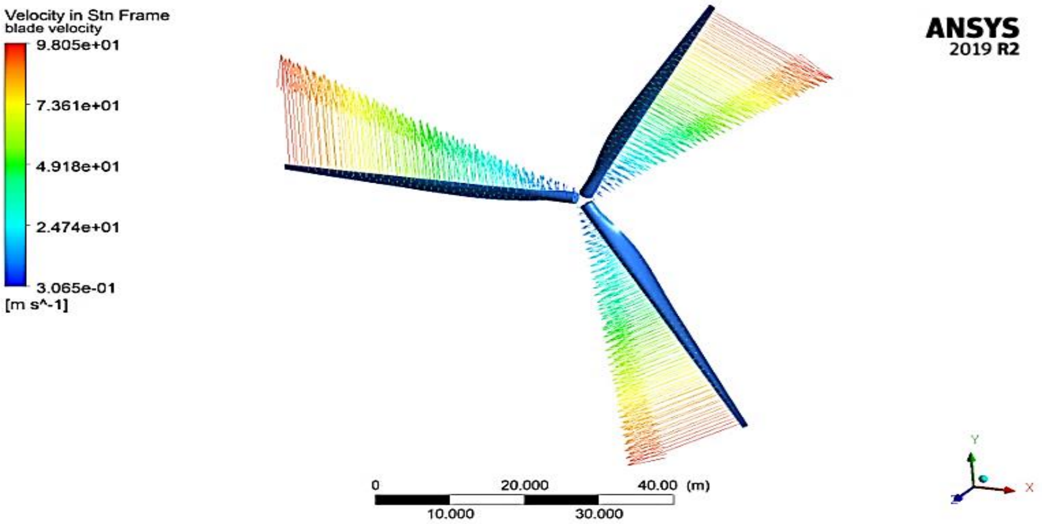


Figure 7. Velocity vector simulation for the blades.

Figure 8 is the contour plot of the velocity magnitude produced by ANSYS software simulating wind turbine blades. The streamline flow, or the direction and speed of the wind blowing across the turbine blade at any particular time, is represented by the colorful lines. The smooth and continuous streamlines in this instance suggest that the flow is laminar, or non-turbulent. To reduce drag and increase lift, rotor blades should be aerodynamically optimized. High lift-to-drag ratio airfoil profiles are frequently employed. Additionally, it’s important to tailor the blade form and twist distribution to the anticipated wind conditions in order to maximize power production. Further, a yaw control system should be installed on the wind turbine to guarantee that the rotor is constantly facing the wind. The flow of the velocity vector is maximized by placing the turbine in the direction of the wind, reducing turbulence, and enhancing overall performance.

A technique used to enhance the aerodynamic performance and efficiency of the turbine is pressure contouring on the blade surface as shown in Figure 9 It is feasible to reduce fatigue loads, boost power output, and minimize aerodynamic losses by carefully planning the pressure distribution throughout the blade. To obtain desirable pressure distributions, the blade surface is shaped throughout the process. This may be accomplished by combining different twist angles, serrated or dimpled surfaces, and airfoil designs. In order to provide maximum lift and minimal drag, a smooth and regulated pressure gradient must be created over the length of the blade.

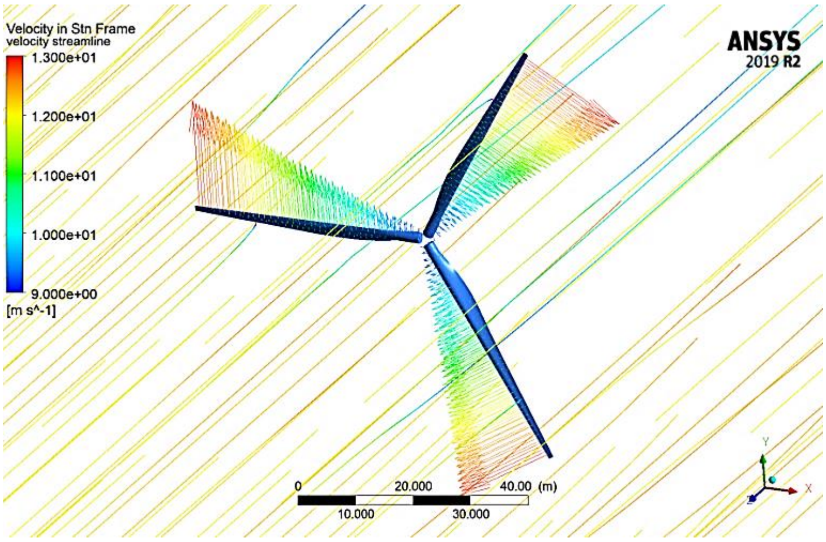


Figure 8. Streamline flow of velocity vector.

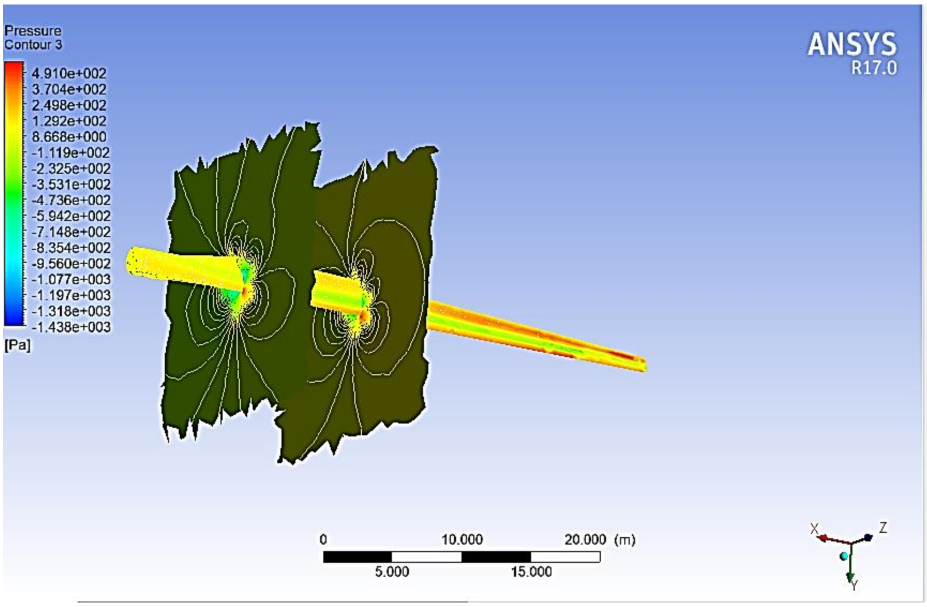


Figure 9. Pressure contouring on blade surface.

A blade wind turbine’s performance and operation are significantly impacted by the wind’s pressure and velocity shown in Figure 10. The power production of a wind turbine is directly impacted by the wind velocity, also known as wind speed. A wind turbine’s output is proportional to the cube of the wind speed. In other words, the power output multiplies by eight if the wind speeds twice. As a result, higher wind speeds often translate into increased power generation. Air density and wind pressure both have an impact on how well a wind turbine performs. Temperature, humidity, and altitude all affect the air density. An increase in air density results in greater air mass per volume, which increases the force pushing on the turbine blades.

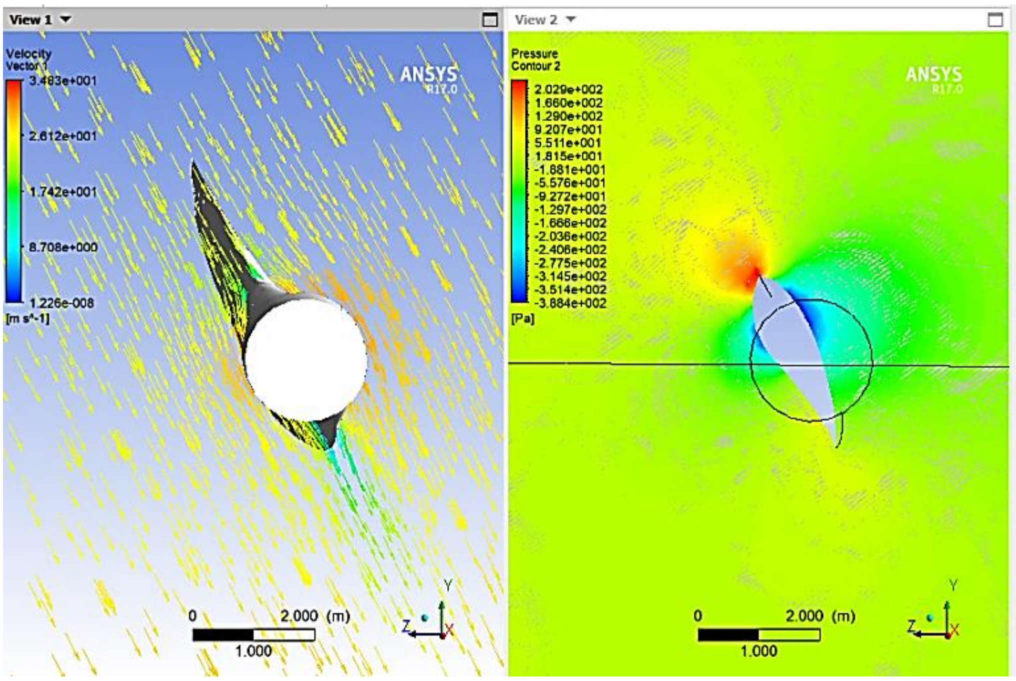


Figure 10. Effect of velocity and pressure on the blade.

Q-Blade is a highly advanced multi-physics code that covers the complete range of aspects required for the aero-servo-hydro-elastic design, prototyping, simulation, and certification of wind turbines. Q-Blade allows you to run highly detailed simulations of any wind turbine design, with superior physics models more than 20x faster than real-time. All this functionality is made accessible in an intuitive and friendly graphical user interface. Figure 11 shows the structural analysis of horizontal axis wind turbine using Q-blade. Q-Blade helps analyze the structural integrity of wind turbine blades under wind, gravity, and centrifugal loads.

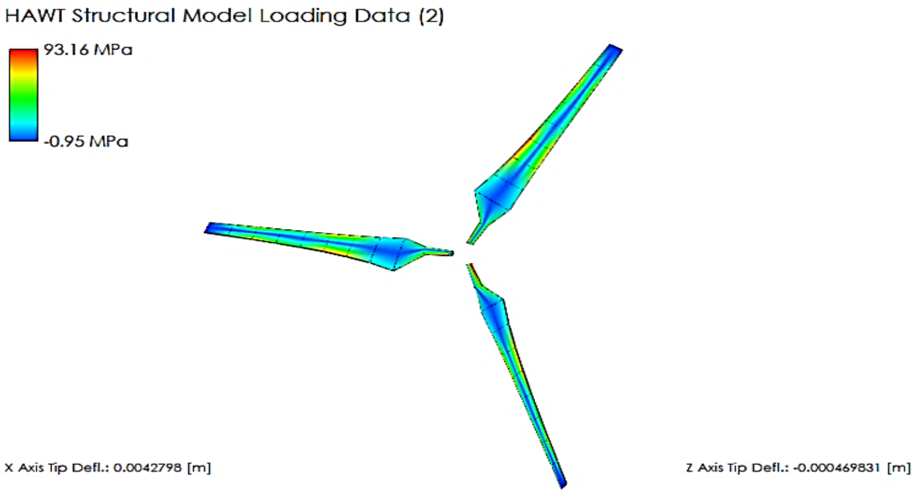


Figure 11. Structural analysis of blades.

Designing and guaranteeing the performance and safety of the wind turbine requires a structural study of the turbine blades. For this purpose, the first stage is to choose the right materials for the construction of the blade. Fiberglass-reinforced composites, carbon fiber composites, and occasionally wood are among the often utilized materials. The mechanical characteristics of the material, including its tensile strength, elastic modulus, and fatigue resistance, are essential elements taken into account throughout the study. Calculating the loads that are placed on the wind turbine blades is the next stage. These loads include gravity loads, centrifugal forces, and dynamic loads brought on by wind turbulence, gusts, and yaw misalignment. Aerodynamic forces (such as wind speed, air density, and turbulence) are also included. The loads are frequently determined using standards and recommendations offered by organizations like the International Electro-technical Commission (IEC).

FEA is a numerical technique that is frequently used in structural analysis. To get stress and deformation distributions, the blade geometry is discretized into tiny components and the governing equations are solved repeatedly. FEA aids in locating vulnerable areas where stress concentrations may develop, such as root and tip sections. Wind turbine blades are subjected to cyclic stress, which over time may cause fatigue failure. Calculating how many load cycles the blade can sustain before failing is a part of the fatigue analysis process. It takes into account things like the applied loads, the material characteristics, and the blade material's S-N (stress-life) curve. It is normally required to access wind data, such as past wind speed measurements or simulated wind data, to create a wind speed contour at a certain height for a wind turbine. It may be helpful to make a contour map that depicts the various wind speeds based on this data.

Wind speed contour is usually created using the wind information, data interpolation, and grid setup shown in Figure 12. Determine the wind speeds at each grid point at the given height using the filtered and interpolated wind speed data. For places without direct observations, wind speeds may be estimated using a variety of mathematical models or interpolation techniques.

A sensitivity analysis was performed to determine how numerous design variables affect the 100KW single rotor horizontal axis wind turbine's output. Blade length, rotor speed, wind speed, air density, pitch angle, and tip speed ratio (TSR) are the main parameters to be considered in the sensitivity analysis. To this purpose, the relationship between Cp and TSR has been shown in Figure 13.

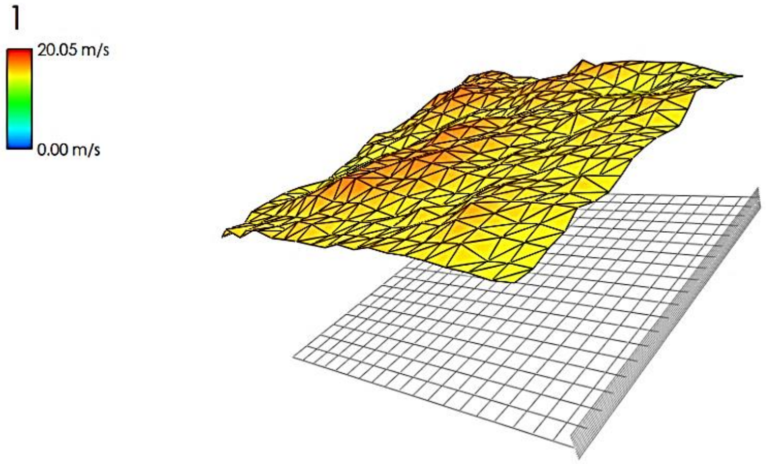


Figure 12. Wind speed contour at certain height.

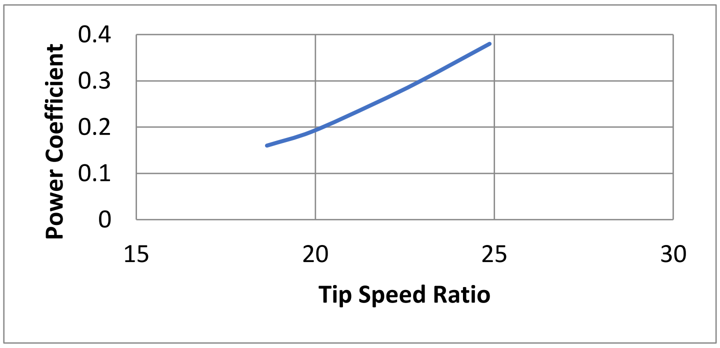


Figure 13. Relation between Cp and TSR.

The graph's increasing trend represents an essential component of wind turbine performance as shown in Figure 13. As the tip speed ratio increases, indicating greater rotational speeds relative to wind speed, the turbine's power extraction efficiency increases. This behavior is caused by aerodynamic variables and dynamic stall occurrences, which affect the turbine blades' capacity of capturing and converting wind energy into mechanical power.

The proposed design for the 100 kW HAWT achieves a Cp close to the theoretical limit (Betz limit), suggesting highly efficient energy capture from the wind. The results of current study may be compared with the 300 kW HAWT designed by Sedaghat and Mirhosseini [11]. The slight difference in results may be attributed to the scale of the turbines and the specific aerodynamic optimizations employed in each design.

6. Conclusions

The presented idea began with a recognition of the critical need for sustainable energy sources, which was fueled by concerns about the environment and a global shift towards cleaner options. The theoretical underpinnings were laid for the rigorous design and analysis of a 100 kW horizontal axis wind turbine (HAWT). The complexities of blade aerodynamics, structural concerns, and fluid dynamics are analyzed by integrating powerful computational tools like SolidWorks and ANSYS, enabling a holistic approach to turbine optimization. From theoretical underpinnings to CFD analyses, every aspect of current research contributed to a comprehensive understanding of wind turbine performance. By studying and performing a detailed analysis of HAWT, the major factors affecting the design and working of HAWT can be predicted. The findings of current research not only contribute to a better knowledge of aerodynamic principles but also help to guide the development of a 100 kW HAWT at a wind speed of approximately 6.9 m/s optimized for efficient and dependable power generation. From the simulation results of ANSYS, it is noted that the maximum turbulence occurs at the tail region of blades due to pressure difference. As we move towards a better future, this research demonstrates wind energy's potential as a significant parameter in the global shift to environmentally friendly clean power sources.

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Author Contributions

Conceptualization, S.A. and M.F.; Methodology, S.A.; Software, M.F.; Validation, S.A., M.F. and Z.A.; Formal Analysis, F.A.; Investigation, M.U.; Resources, S.A.; Data Curation, S.A.; Writing—Original Draft Preparation, M.F.; Writing—Review & Editing, M.F.; Visualization, F.A.; Supervision, S.A.; Project Administration, S.A.; Funding Acquisition, M.F.

Ethics Statement

Not applicable for this study as it does not involve humans or animals.

Informed Consent Statement

Not applicable for this study as it does not involve humans.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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