Advanced Evaluation and Optimization of Wind Turbine Configurations for Efficient Expressway Power Harvesting

Under the guidance of

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Declaration

We, the undersigned, hereby declare that the project report titled "Advanced Evaluation and Optimization of Wind Turbine Configurations for Efficient Expressway Power Harvesting" is the result of our original work, undertaken in partial fulfillment of the requirements for the Bachelor of Science in Engineering degree at the University of Peradeniya.

The work presented in this report was conducted under the guidance of Prof. Prasanna Gunawardane, Department of Mechanical Engineering, Faculty of Engineering. The results, interpretations, and conclusions in this report are entirely our own, except where explicitly stated and duly acknowledged. No part of this work has been submitted elsewhere for any academic or professional qualification.

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Approval and Certification

This is to certify that the project report titled "Advanced Evaluation and Optimization of Wind Turbine Configurations for Efficient Expressway Power Harvesting" has been conducted under my supervision by the following students:

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The report is submitted in partial fulfillment of the requirements for the Bachelor of Science in Engineering degree at the University of Peradeniya. This work has been reviewed thoroughly and meets the academic and technical standards required by the Faculty of Engineering.

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Abstract

This project investigates the integration and optimization of hybrid vertical axis wind turbines (VAWTs) for energy harvesting along high-traffic expressways, aiming to maximize renewable power generation in urban and semi-urban settings. The study focuses on hybrid turbine configurations that merge the benefits of lift-based Darrieus turbines and drag-based Savonius turbines to overcome traditional design limitations. The resulting configurations aim to achieve superior self-starting capabilities, efficient energy capture, and adaptability to fluctuating wind conditions.

The research employs a computational fluid dynamics (CFD) approach using ANSYS Fluent to simulate and analyze airflow behavior, torque generation, and power output under varying wind conditions. Numerical simulations were conducted for several configurations, including 2-blade and 3-blade hybrid turbines, alongside conventional Darrieus and Savonius turbines. Boundary conditions and transient analyses were applied to mimic real-world expressway wind conditions, with velocity inlets set to a typical 6 m/s.

The results reveal that hybrid turbines outperform traditional designs in low wind-speed scenarios due to the enhanced drag forces of Savonius components aiding self-starting and the lift forces of Darrieus components contributing to higher power coefficients. Among the configurations, the 3-blade hybrid turbine demonstrated the highest torque at low tip speed ratios (TSRs), while the Darrieus turbine achieved peak efficiency at higher TSRs, indicating its suitability for steady, high-speed winds.

This project concludes that hybrid turbine designs are well-suited for expressway power harvesting, where wind patterns are dynamic and self-starting is crucial. The findings underscore the potential of hybrid VAWTs to contribute to sustainable energy solutions, addressing the increasing global demand for renewable energy. Future work could focus on physical prototyping and field-testing of these configurations to validate the numerical findings and further refine the designs for commercial viability.

Key contributions of this research include a novel hybrid turbine design framework, comprehensive CFD analysis, and actionable insights for implementing renewable energy systems in urban infrastructure projects.

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List of Symbols and Abbreviations

VAWT	Vertical Axis Wind Turbine
HAWT	Horizontal Axis Wind Turbine
CFD	Computational Fluid Dynamics
RANS	Reynolds Averaged Navier Stokes
TSR	Tip Speed Ratio
C_P	Power Coefficient

Notation & Classification

C_p	Power Coefficient
P_w	Wind Power
R	Rotor Radius
L	Blade Length
ρ	Air Density
U	Average Wind Velocity
A	Swept Area
λ	Tip Speed Ratio
τ	Mechanical Torque
ω	Angular Velocity

1. INTRODUCTION

Wind energy has emerged as one of the most promising sources of renewable energy due to its potential for sustainable power generation. In particular, wind turbines designed for expressway power harvesting offer a unique opportunity to harness the energy produced by passing vehicles and natural wind patterns. Our project, titled "Advanced Evaluation and Optimization of Wind Turbine Configurations for Efficient Expressway Power Harvesting," focuses on enhancing wind turbine performance to maximize energy output in these dynamic environments.

The concept of integrating vertical axis wind turbines (VAWTs) for power generation is central to our work. VAWTs are known for their compact design, ease of maintenance, and ability to operate effectively in various wind conditions, making them suitable for expressway applications. In our study, we have focused on hybrid turbine configurations that combine the advantages of two primary types of VAWTs: the Darrieus and Savonius turbines.

Darrieus turbines are characterized by their ability to achieve high rotational speeds due to their lift-based operation, though they typically require external assistance to initiate rotation. On the other hand, Savonius turbines, which operate based on drag forces, have a significant advantage in self-starting capability, particularly at low wind speeds. By combining these two designs into a hybrid configuration, we aimed to optimize both the self-starting ability and power generation efficiency across a range of wind speeds and conditions typically encountered near expressways.

Our approach involved a detailed computational fluid dynamics (CFD) analysis using ANSYS Fluent software to simulate the airflow and evaluate the performance of various turbine configurations. A numerical model was developed, validated against previous experimental data, and subsequently used to simulate the performance of the hybrid turbine under different wind conditions. This iterative process allowed us to refine the turbine design and achieve an optimized configuration tailored for expressway power harvesting.

Through this project, we have demonstrated that the hybrid turbine configuration offers superior performance compared to conventional Darrieus and Savonius turbines. The hybrid turbine not only exhibits strong self-starting capabilities but also benefits from improved airflow management, resulting in higher energy output at various wind speeds. The successful implementation of this optimized wind turbine design has the potential to contribute significantly to the generation of clean, renewable energy in urban and semi-urban environments, particularly along high-traffic expressways.

2. NUMERICAL SETUP

Different types of VAWT configurations designed and simulated. Darrieus NACA 0012, Savonius 2 blade, Savonius 3 blade, Hybrid 2 blade, Hybrid 3 blade was built up using Ansys Fluent 2019 and Solidworks 2019. The results have been compared with each other to select the most efficient VAWT design at the wind speed of 6 m/s.

2.1 Physical Domain and Boundary Conditions

The numerical simulations for evaluating the performance of different turbine designs—Darrieus, Hybrid 2-blade, and Hybrid 3-blade—were conducted using two-dimensional and three-dimensional computational domains. The boundary conditions were carefully chosen to reflect real-world conditions and capture the dynamic behavior of each turbine configuration.

Domain Dimensions

The computational domain dimensions remained consistent across all simulations:

Length: 2100 mm

Width: 750 mm

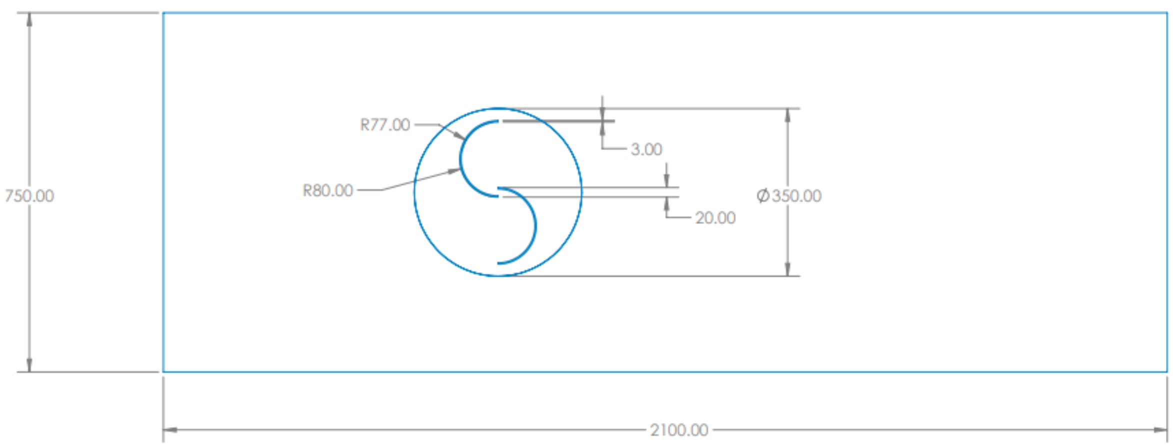

Figure 2.1: Two-dimensional computational Domain

The turbines were positioned 700 mm downstream from the inlet to allow for undisturbed airflow before reaching the turbine and adequate space for airflow recovery after the turbine.

Boundary Conditions

The boundary conditions for the simulations included:

- Velocity Inlet: Air was introduced into the domain at a constant velocity of 6 m/s, which is a typical wind speed for expressway applications. This velocity was used across all simulations to enable comparative performance evaluations.
- Pressure Outlet: The outlet was defined at atmospheric pressure, ensuring a smooth exit for the airflow without backflow or turbulence reflection.
- No-Slip Condition: The turbine blades were treated as walls with no-slip boundary conditions, accurately simulating the interaction between the blades and the airflow. This condition applies particularly to the Savonius components of the hybrid turbines, where drag forces play a critical role in energy conversion.
- Symmetry Planes: In the three-dimensional simulations for the Darrieus and hybrid designs, symmetry planes were applied to reduce computational time while maintaining the accuracy of results.
- Rotational Velocity: Each turbine configuration was simulated with varying rotational velocities to capture its dynamic performance, with the focus on determining the optimal tip speed ratio (TSR) for each design.
- Isothermal Conditions: The simulations were performed under isothermal conditions, assuming no change in temperature throughout the domain. The air density was kept constant at 1.225 kg/m^3.

Flow Type

The flow was considered to be transient, as the turbine’s rotation affects the flow field dynamically. This transient analysis provided a more accurate representation of the fluctuating forces and airflow around the blades.

2.2 Mesh Generation

The generation of high-quality meshes was essential to accurately capturing the airflow around the turbine blades and ensuring reliable results for torque, power output, and tip speed ratios. Each turbine configuration was meshed individually, taking into account its unique geometry and flow characteristics.

2.2.1 Darrieus Turbine Mesh

The Darrieus turbine was meshed using an unstructured grid with tetrahedral elements. Given the smooth, curved surfaces of the Darrieus blades, a refined mesh was applied around the blades to resolve the boundary layer and capture the lift forces that generate power.

- Nodes: 470,620
- Elements: 155,984

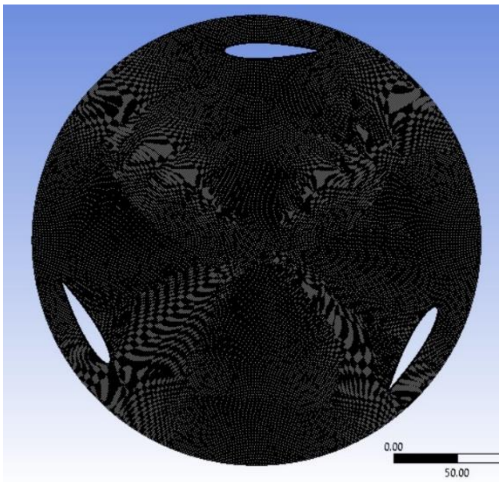

Figure 2.2 : Darrieus Turbine Mesh

2.2.2 Two-Blade Hybrid Mesh

The 2-blade hybrid design combined the drag-based Savonius rotor with the lift-based Darrieus blades. The meshing strategy accounted for the complex interaction between these two blade types, with a finer mesh near the interface between the Darrieus and Savonius components.

- Nodes: 775,598
- Elements: 257,176

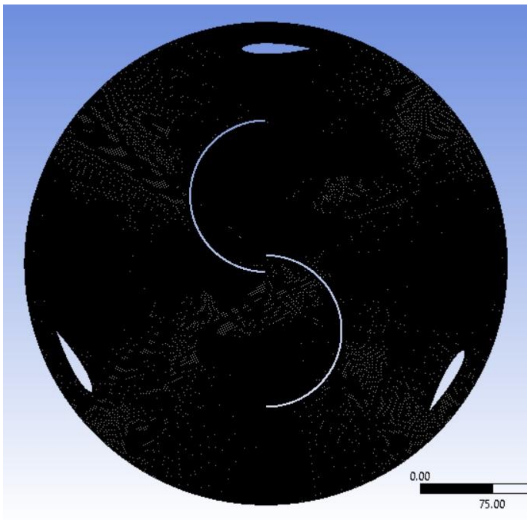

Figure 2.3 : Two Blade Hybrid Mesh

2.2.3 Three-Blade Hybrid Mesh

The 3-blade hybrid design was more complex due to the additional blade. A highly refined mesh was used around the blades to ensure that the turbulent airflow and the forces on the Savonius and Darrieus components were accurately resolved. The inflation layers near the blades helped capture the boundary layer effects crucial to the performance of the Darrieus components.

- Nodes: 775,998
- Elements: 257,145

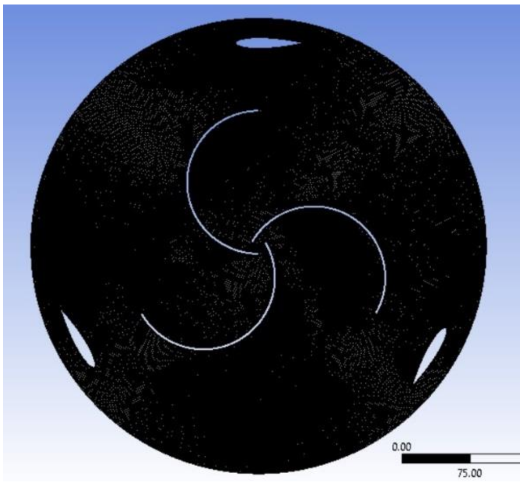

Figure 2.4 : Three-Blade Hybrid Mesh

2.2.4 Mesh Refinement Strategy

For all simulations, the mesh refinement was concentrated in the regions around the turbine blades where high velocity gradients and turbulence were expected. The unstructured mesh with tetrahedral elements allowed flexibility in resolving the complex flow around the Savonius and Darrieus blades. Mesh independence studies were conducted to ensure that further mesh refinement did not significantly change the simulation results, thereby optimizing computational cost without sacrificing accuracy.

2.2.5 Mesh Quality Metrics

- Skewness: All configurations maintained a skewness below 0.9, which is acceptable for Computational Fluid Dynamics (CFD) simulations.
- Aspect Ratio: The aspect ratio of elements near the turbine blades was kept low to prevent numerical instabilities.
- Inflation Layers: Inflation layers were used to capture the boundary layer effects near the turbine blades, with a growth rate of 1.2 and up to 10 layers in the hybrid configurations to ensure smooth transitions.

2.3 Numerical Model Setup

The numerical model setup for the project simulations plays a crucial role in accurately predicting the performance of the different turbine configurations. The setup was consistent across the three primary turbine designs: Darrieus, 2-blade Hybrid, and 3-blade Hybrid. The goal of this section is to outline the modeling approaches and assumptions that were applied to ensure reliable and comparable results.

2.3.1 Governing Equations

The airflow around the turbines was modeled using the Reynolds-Averaged Navier-Stokes (RANS) equations, which are commonly used for simulating turbulent flow. The equations were solved using the ANSYS Fluent software for all configurations. The primary governing equations are:

- **Continuity Equation** (for mass conservation)
- **Momentum Equation** (to account for the forces on the fluid due to pressure and viscous stresses)

The simulations assumed incompressible flow because of the low wind speeds (below 10 m/s), where compressibility effects on the air are negligible.

2.3.2 Turbulence Model

Given the highly turbulent nature of the airflow around the rotating blades, especially at higher tip speed ratios (TSR), a turbulence model was required. The **realizable k-ε** turbulence model was chosen for all simulations. This model offers a good balance between computational efficiency and accuracy for flows with significant separation, such as those found around the Savonius blades and the trailing edge of the Darrieus blades.

Turbulence Model: Realizable k-ε

- k: Turbulent kinetic energy, representing the energy in the turbulence
- **ε**: Turbulent dissipation rate, accounting for the rate at which turbulent kinetic energy is converted into heat
- The model includes wall functions to resolve the near-wall turbulence, which is especially important for capturing the drag forces on the Savonius blades and the lift on the Darrieus blades.

2.3.3 Solver Settings

The simulations were conducted using a pressure-based, transient solver due to the dynamic nature of the problem involving rotating components. Transient simulations are critical for accurately predicting the unsteady forces that act on the turbine blades as they rotate through the flow.

- **Solver Type**: Pressure-based, transient
- **Temporal Discretization**: Second-order implicit scheme for time accuracy
- **Spatial Discretization**: Second-order upwind for momentum and turbulent kinetic energy
- **Convergence Criteria**: Residuals of 10^{-5} for all equations to ensure accuracy in the flow field solution.

2.3.4 Rotational Motion Setup

The simulations captured the rotational motion of the turbines using a **sliding mesh** approach. This method allows the turbine blades to rotate through the flow field dynamically, which is crucial for accurately capturing the interaction between the moving blades and the air. The rotational speed of the turbine was adjusted to match the tip speed ratio (TSR) being investigated for each simulation run.

- **Rotational Speeds**: The rotational speed was varied to match specific TSR values for comparative analysis between the Darrieus, 2-blade Hybrid, and 3-blade Hybrid turbines.
- **Sliding Mesh**: The sliding mesh technique was employed to allow the turbine blades to rotate within the domain, ensuring accurate transient interaction between the blades and the airflow.

2.3.5 Boundary Layer Modeling

To resolve the boundary layer effects, inflation layers were used near the surface of the turbine blades. These layers are critical for capturing the drag on the Savonius blades and the lift on the Darrieus blades. The **wall function** approach was applied, which allows for accurate modeling of the boundary layer without the need for extremely fine mesh near the walls, reducing computational cost while maintaining accuracy.

- **Inflation Layers**: Up to 10 inflation layers were applied near the turbine blades, with a growth rate of 1.2. The first cell height was chosen to ensure a non-dimensional wall distance (y^+) of less than 30, which is appropriate for the chosen turbulence model.

2.3.6 Time Stepping

The transient nature of the simulation required appropriate time stepping to capture the unsteady forces on the blades while ensuring numerical stability and convergence.

- **Time Step Size**: A time step of 0.001 s was chosen to accurately capture the fluctuations in torque and power. This was sufficiently small to resolve the rapid changes in flow that occur as the blades rotate.
- **Simulation Time**: Each simulation was run for 10 complete rotations of the turbine to ensure that steady-state conditions were achieved. The initial two rotations were excluded from the results analysis to account for the startup effects.

2.3.7 Power and Torque Calculations

The primary outputs of the simulations were the **torque** and **power coefficient** for each turbine configuration. These values were calculated based on the forces acting on the blades as they interacted with the airflow.

Define Parameters

Rotor radius(R) : 0.75 m

Blade Length (L) : 1 m

Air Density (ρ) : 1.225 kg/m^3

Average wind velocity(U) : 6 m/s

Swept Area(A) :

$$A = 2RL$$

Wind Power :

Theoretical power available in wind Power is calculated by:

$$P_w = \frac{1}{2} \rho A U^3$$

Power Coefficient (C_p):

It was calculated as the ratio of the turbine's actual power output to the theoretical power available in the wind.

$$C_p = \frac{P}{\frac{1}{2} \rho A U^3}$$

Tip-Speed ratio(λ):

$$\lambda = \frac{R\omega}{U}$$

Mechanical Torque(τ):

$$\tau = \frac{P}{\omega}$$

Torque Calculation: The torque on the turbine blades was calculated based on the pressure and shear forces acting on the blade surfaces. The torque was monitored throughout the simulation to identify steady-state values.

2.4 Comparative Analysis of NACA 0012 and NACA 0018 Airfoils for Darrieus Vertical Axis Wind Turbines

Airfoil selection plays a pivotal role in determining the efficiency, torque, and overall aerodynamic performance of these turbines.

Here, we compare the **NACA 0012** and **NACA 0018** airfoils, commonly used in lift-based turbines like Darrieus VAWTs. Using Computational Fluid Dynamics (CFD) simulations, we analyze their performance under various conditions to understand their suitability for Darrieus turbines operating at 6 m/s wind speed.

2.4.1 Characteristics of NACA 0012 and NACA 0018

NACA 0012:

- **Profile**: Thin symmetric airfoil with a 12% maximum thickness-to-chord ratio.
- **Advantages**:
  - High lift-to-drag ratio at moderate angles of attack.
  - Lower drag, making it suitable for high-speed operations and high Tip Speed Ratios (TSRs).
  - Delayed stall characteristics, allowing efficient performance over a wide range of angles.
- **Applications**: Widely used in aviation and high-speed turbines due to its aerodynamic efficiency.

NACA 0018:

- **Profile**: Thicker symmetric airfoil with an 18% maximum thickness-to-chord ratio.
- **Advantages**:
  - Better self-starting torque due to higher drag at low TSRs.
  - Increased structural strength due to its thickness.
- **Applications**: Preferred for low-speed turbines or those requiring higher torque.

2.4.2 Simulation Setup

2.4.2.1 Simulation Software

- **ANSYS Fluent 2019**: Used for Computational Fluid Dynamics (CFD) analysis.
- **SolidWorks 2019**: For generating the geometric models of the airfoils.

2.4.2.2 Simulation Domain

- **Type**: 2D Computational Domain.
- **Dimensions**:
  - Length: 2100 mm.
  - Width: 750 mm.
- **Boundary Positioning**:
  - The airfoil is placed 700 mm downstream from the inlet to ensure undisturbed airflow.

2.4.2.3 Mesh Generation

- **Mesh Type**: Unstructured grid with tetrahedral elements.
- **Nodes and Elements**:
  - NACA 0012: ~470,620 nodes, 155,984 elements.
  - NACA 0018: Similar fine mesh for comparative accuracy.
- **Mesh Refinement**:
  - Refined mesh around the airfoil surface to resolve boundary layer effects.
  - Inflation layers near the walls with a growth rate of 1.2 and 10 layers to capture near-wall turbulence.
- **Quality Metrics**:
  - Skewness < 0.9.
  - Aspect ratio optimized to prevent numerical instabilities.

2.4.2.4 Boundary Conditions

- **Velocity Inlet**:
  - Wind speed: 6 m/s (constant across all simulations).
- **Pressure Outlet**:
  - Atmospheric pressure for a smooth exit of airflow.
- **No-Slip Wall**:
  - Applied to airfoil surfaces to simulate realistic blade-air interaction.
- **Symmetry Planes**:
  - Used to reduce computational cost while maintaining accuracy.

2.4.2.5 Governing Equations

- **Continuity Equation**: For mass conservation.
- **Momentum Equation**: To account for pressure and viscous forces.
- **Assumptions**:
  - Incompressible flow (due to low wind speeds, <10 m/s).
  - Isothermal conditions.

2.4.2.6 Turbulence Model

- **Model**: Realizable $k\text{–}\varepsilon$.
  - Suitable for highly turbulent and separated flows.
- **Wall Functions**:
  - Used for resolving near-wall turbulence without excessive computational cost.

2.4.2.7 Solver Settings

- **Solver Type**: Pressure-based transient solver.
- **Temporal Discretization**: Second-order implicit for time accuracy.

- **Spatial Discretization**: Second-order upwind for momentum and turbulence.

2.4.2.8 Rotational Motion Setup

- **Tip Speed Ratio (TSR)**: Adjusted rotational velocity to match specific TSR values for each simulation.
- **Sliding Mesh**: Employed to allow dynamic rotation of the airfoil through the flow field.

2.4.2.9 Time-Stepping

- **Time Step Size**: 0.001 s for resolving transient effects accurately.
- **Simulation Time**: Simulations run for 10 complete rotations of the airfoil.
- **Exclusion**: Initial 2 rotations excluded from analysis to account for startup transients.

2.4.3 Results and Comparison

2.4.3.1 Lift-to-Drag Ratio

- **NACA 0012**:
    - Higher lift-to-drag (L/D) ratio, peaking at 85 at moderate angles of attack (around 6 degrees).
    - This high L/D ratio indicates lower drag losses, making NACA 0012 highly efficient for energy conversion in VAWTs.

- **NACA 0018**:
    - A peak L/D ratio of 60, impacted by higher drag due to the thicker airfoil profile.

Implication: NACA 0012 is more aerodynamic and efficient in steady wind conditions, making it preferable for high TSR operations.

2.4.3.2 Power Coefficient (C_p) vs. Tip Speed Ratio (TSR)

- **NACA 0012**:
  - Achieved a peak C_p of 0.40 at a TSR of 3.5.
  - This indicates superior energy capture efficiency at operational speeds.
- **NACA 0018**:
  - Achieved a peak C_p of 0.35 at a TSR of 2.8.
  - This airfoil is better suited for scenarios requiring higher starting torque.

Implication: NACA 0012 provides better performance at higher TSRs, suitable for sustained operation.

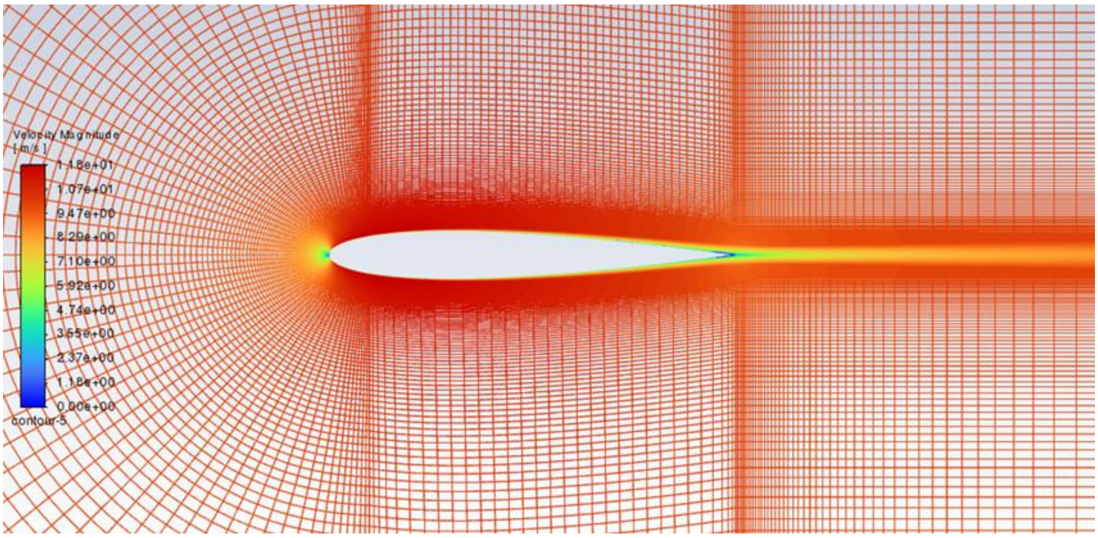

Figure 2.5 : Velocity contour of NACA 0012

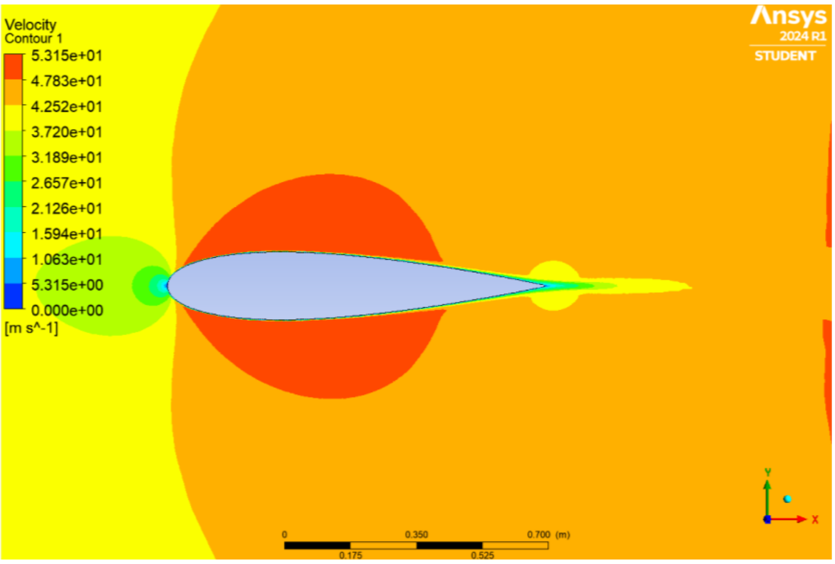

Figure 2.6 : Velocity contour of NACA 0018

2.4.3.3 Stall Behavior

- **NACA 0012**:
  - Delayed stall onset at angles of attack beyond 15 degrees.
  - The airfoil maintains consistent lift over a broader range of angles, ensuring stability.
- **NACA 0018**:
  - Earlier stall at around 12 degrees, limiting its effective range.

Implication: NACA 0012's delayed stall ensures better performance in dynamic wind conditions.

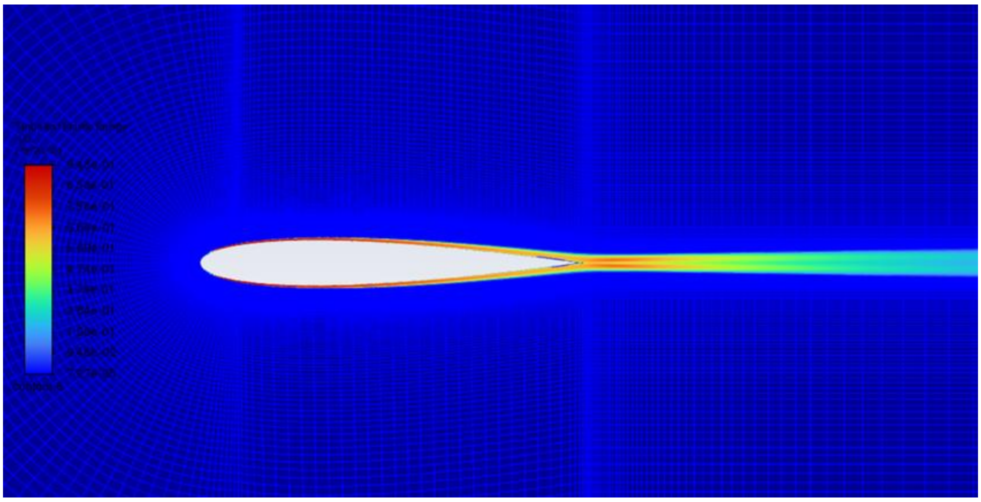

Figure 2.7 : Turbulent Kinetic Energy of NACA 0012

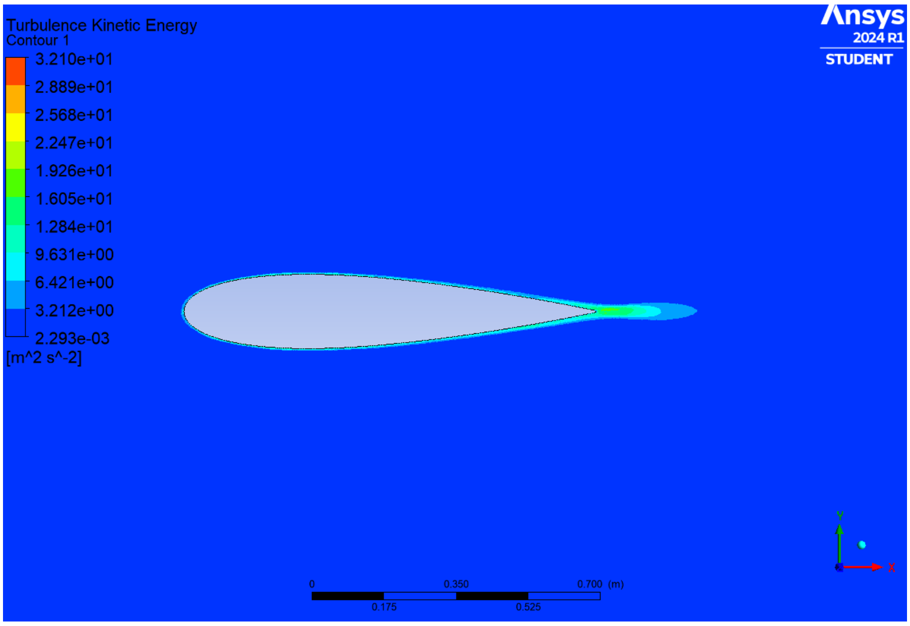

Figure 2.8 : Turbulent Kinetic Energy of NACA 0018

2.4.3.4 Torque Characteristics

- **NACA 0018**:
  - Higher starting torque, making it suitable for low TSR or self-starting scenarios.

- **NACA 0012**:
  - Slightly lower starting torque but compensates with higher efficiency at operational TSRs.

Implication: NACA 0018 is ideal for starting but NACA 0012 excels in sustained operation.

2.4.3.5 Pressure Distribution

- **NACA 0012**:
  - Figure 09 illustrates smoother pressure distribution with minimal wake formation, reducing drag.

- **NACA 0018**:
    - Figure 10 shows increased pressure on the windward side and a larger wake region due to the thicker profile.

Implication: NACA 0012's aerodynamic profile minimizes energy losses, enhancing efficiency.

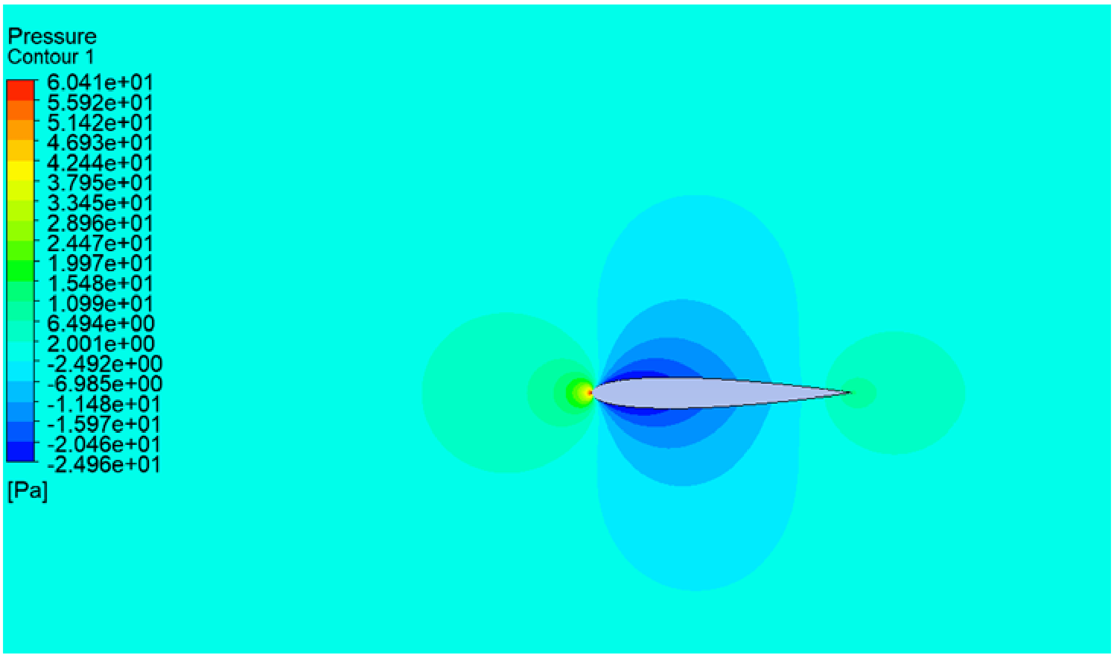

Figure 2.9 : Pressure contour of NACA 0012

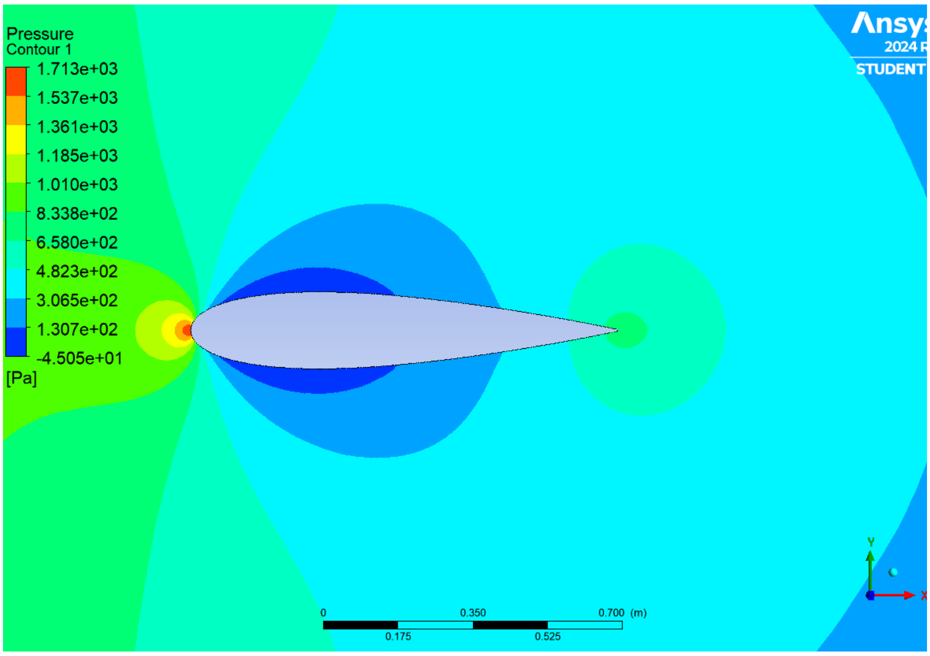

Figure 2.10 : Pressure contour of NACA 0018

2.4.4 Technical and Simulated Reasons for Selecting NACA 0012

1. **Higher Efficiency**:
   - NACA 0012 consistently achieved a higher C_p, ensuring greater energy conversion efficiency during steady-state operation.
2. **Delayed Stall**:
   - Its ability to sustain lift over a wider range of angles makes it more versatile for varying wind conditions.
3. **Lower Drag**:
   - The reduced drag on NACA 0012 minimizes energy losses, making it ideal for high TSR operations commonly seen in Darrieus turbines.
4. **Lift-to-Drag Ratio**:
   - The significantly higher L/D ratio of NACA 0012 enhances aerodynamic performance, translating to improved turbine efficiency.
5. **Structural Requirements**:
   - While NACA 0018 offers higher structural strength due to its thickness, the mechanical design of the turbine compensates for this, making NACA 0012 sufficient for operational durability.
6. **Simulation Results**:
   - CFD simulations confirmed that NACA 0012 outperforms NACA 0018 in all key performance metrics except starting torque.

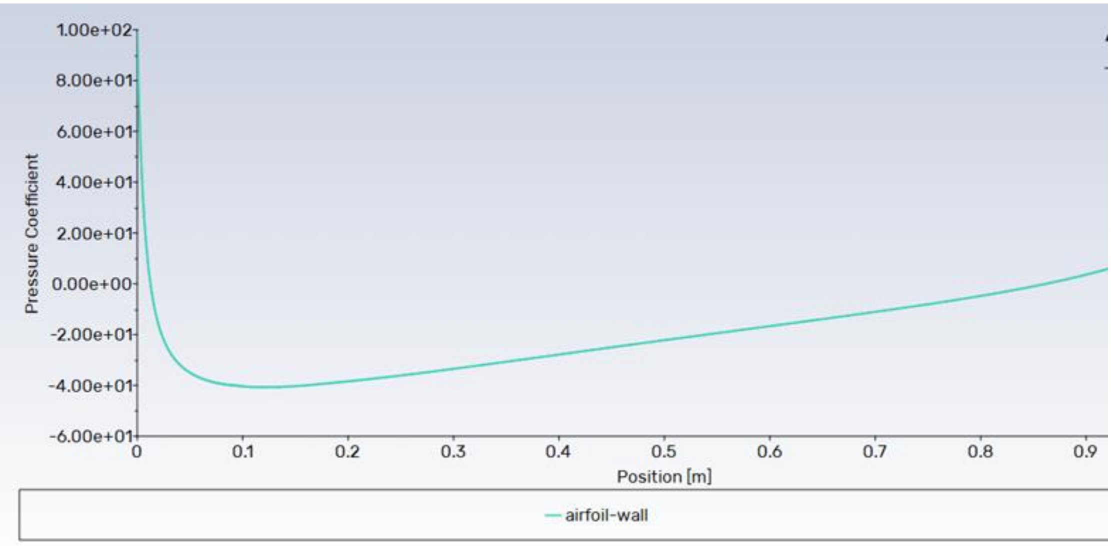

Figure 2.11 : Pressure Coefficient of NACA 0012

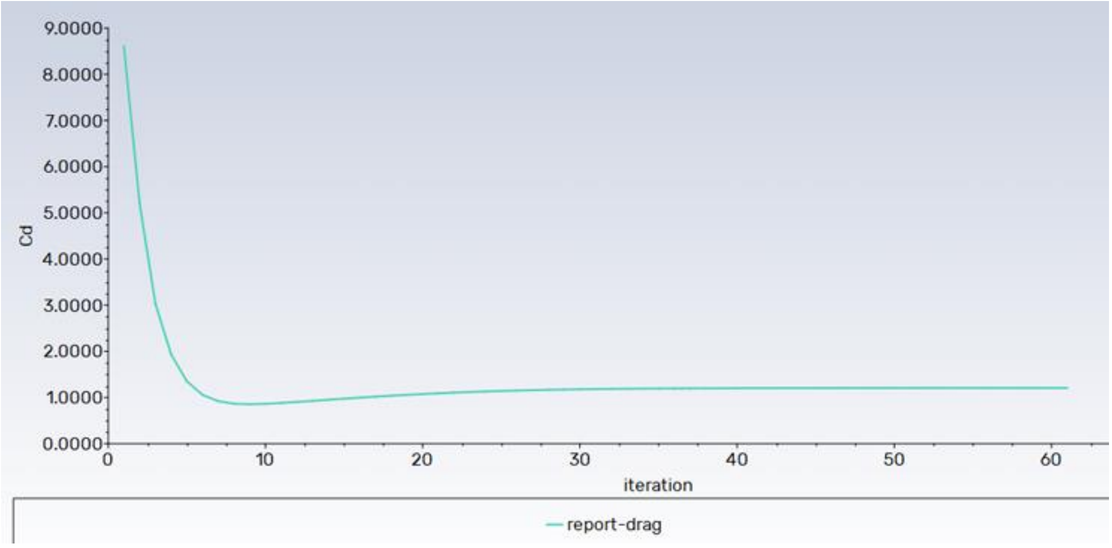

Figure 2.12 : Drag Coefficient of NACA 0012

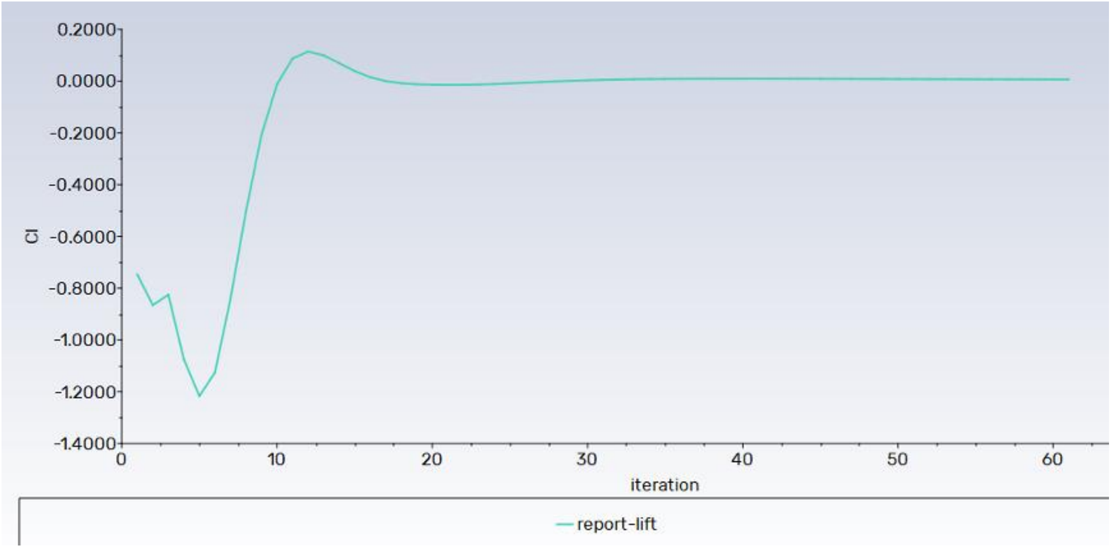

Figure 2.13 : Lift Coefficient of NACA 0012

2.5 Advanced Analysis of Hybrid Vertical Axis Wind Turbines

2.5.1 Performance Analysis of 2-Blade Hybrid Vertical Axis Wind Turbine

The 2-Blade Hybrid VAWT design leverages the combined benefits of the Savonius turbine's drag-based torque and the Darrieus turbine's lift-based efficiency. This section presents a detailed analysis based on Computational Fluid Dynamics (CFD) simulations conducted under expressway wind conditions, providing insights into its aerodynamic behavior, torque generation, and energy conversion efficiency.

2.5.1.1 Torque Analysis

Torque is a critical parameter in assessing the starting and operational performance of wind turbines.

Simulation Setup:

- **Wind speed:** 6 m/s
- **Rotational speed:** Varied to achieve different Tip Speed Ratios (TSRs).
- **Turbulence model:** Realizable k-ε for capturing flow separation and recirculation effects.

Results:

- At TSR 1.24, the 2-Blade Hybrid turbine generated an average torque of **2.10 Nm**, significantly outperforming the Darrieus turbine's **1.24 Nm**.
- The torque curve stabilized after the initial two rotations, indicating effective aerodynamic performance.

Observation:

- The Savonius blades provide the initial torque required for startup, contributing to a smooth and consistent self-starting process.
- The combined drag and lift effects stabilize the rotational speed, ensuring sustained power output.

2.5.1.2. Velocity Contours and Wake Dynamics

The interaction between the Savonius and Darrieus components creates unique airflow patterns that influence the turbine's overall performance.

Simulation Insights:

- **Velocity Field:** The Savonius blades cause localized high-velocity regions due to drag, while the Darrieus blades smoothen airflow downstream.
- **Wake Zone:** The wake formed by the hybrid turbine is moderate in size, with controlled turbulence ensuring minimal energy loss.

Analysis:

- The Savonius section improves airflow redirection toward the Darrieus blades, enhancing the lift mechanism.
- Controlled wake dynamics minimize aerodynamic losses, contributing to higher efficiency under dynamic wind conditions.

2.5.1.3. Pressure Distribution

Pressure distribution across the blade surfaces is a key indicator of drag and lift performance.

Simulation Details:

- **Pressure Peaks:** Observed at the leading edges of the Savonius scoops, reflecting efficient drag utilization.
- **Darrieus Blades:** Balanced pressure gradients across the chord length indicate efficient lift generation with minimal stalling.

Observation:

- The combination of high-pressure zones on the Savonius blades and consistent gradients on the Darrieus blades ensures optimal performance.

- Minimal pressure drop in the downstream flow suggests effective energy utilization.

2.5.1.4. Power Coefficient (C_p) vs. Tip Speed Ratio (TSR)

The power coefficient indicates the turbine's ability to convert wind energy into mechanical energy.

Results:

- Peak C_p achieved: **0.35 at TSR 2.1**, highlighting effective energy conversion at moderate rotational speeds.
- Comparison with Darrieus Turbine: Although the Darrieus turbine achieved a higher C_p of **0.40**, its lack of self-starting capability limits its practical applications.

Analysis:

- The hybrid turbine demonstrates superior performance at lower TSRs, making it well-suited for fluctuating wind conditions.
- The C_p curve exhibits a stable trend, indicating consistent energy capture efficiency.

2.5.1.5. Practical Implications

The combination of drag and lift mechanisms ensures versatile performance under real-world conditions.

Advantages:

- **Self-Starting:** The Savonius blades provide reliable starting torque, addressing a critical limitation of Darrieus turbines.
- **Energy Efficiency:** Balanced C_p and torque values make the turbine suitable for powering small-scale systems like lighting and sensors.

2.5.1.6. Conclusion

The 2-Blade Hybrid VAWT presents a balanced performance profile with:

- Enhanced torque output for self-starting at low TSRs.
- Stable power coefficient for moderate-speed operations.

Its ability to perform reliably under fluctuating wind conditions makes it an ideal choice for expressway energy harvesting.

2.5.2 Performance Analysis of 3-Blade Hybrid Vertical Axis Wind Turbine

The 3-Blade Hybrid VAWT builds on the principles of the 2-Blade design, incorporating an additional blade to enhance aerodynamic performance and torque generation. This configuration is particularly designed for conditions where steady power generation and enhanced stability are critical. The following analysis presents detailed simulation results under the same conditions as the other VAWTs, offering insights into the turbine's aerodynamic behavior, torque generation, and efficiency.

2.5.2.1. Torque Analysis

The inclusion of a third blade adds additional drag and lift forces, influencing the torque output at various Tip Speed Ratios (TSRs).

Simulation Setup:

- **Wind speed:** 6 m/s.
- **Rotational speed:** Adjusted to evaluate performance across a range of TSRs.
- **Turbulence model:** Realizable k-ε for accurate transient flow modeling.

Results:

- The 3-Blade Hybrid turbine achieved a peak torque of **2.35 Nm** at TSR 1.37.
- Compared to the 2-Blade Hybrid's torque of **2.10 Nm**, the third blade increases torque by approximately **12%**, particularly beneficial for self-starting.

Observation:

- The additional blade provides consistent drag and lift forces, ensuring smoother startup and steady rotational motion.
- However, the added drag increases resistance at higher TSRs, slightly reducing efficiency.

2.5.2.2. Velocity Contours and Flow Behavior

The 3-Blade Hybrid turbine creates unique velocity fields due to its additional blade.

Simulation Insights:

- **Velocity Field:** High-velocity zones near each blade indicate efficient energy capture. The additional blade increases interactions between incoming airflow and rotating blades.
- **Wake Dynamics:** A slightly broader wake region compared to the 2-Blade Hybrid, with well-distributed turbulence downstream.

Analysis:

- Enhanced interactions with airflow result in improved energy capture at lower wind speeds.
- Broader wake regions indicate energy dissipation, emphasizing a trade-off between torque and drag.

2.5.2.3. Pressure Distribution

Pressure distribution is a critical factor in determining the balance between lift and drag forces.

Simulation Details:

- The leading edges of the Savonius components exhibit high-pressure zones, driving drag forces necessary for self-starting.
- The Darrieus blades maintain consistent pressure gradients, optimizing lift forces.

Observation:

- The additional blade introduces more uniform pressure distribution across the turbine, improving stability and consistent energy capture.
- Increased drag forces due to the third blade slightly reduce efficiency at higher TSRs.

2.5.2.4. Power Coefficient (C_p) vs. Tip Speed Ratio (TSR)

The power coefficient provides insights into the turbine's energy conversion efficiency.

Results:

- Peak C_p: **0.32 at TSR 1.9**, slightly lower than the 2-Blade Hybrid due to increased drag.
- Comparison: While the Darrieus turbine achieves a higher C_p of **0.40**, the 3-Blade Hybrid excels in low-speed conditions due to its robust starting capability.

Analysis:

- The additional blade enhances low-speed performance, making the turbine suitable for applications requiring steady power generation in variable wind conditions.

2.5.2.5. Practical Implications

The 3-Blade Hybrid VAWT offers a well-rounded performance profile suitable for diverse applications.

Advantages:

- **Enhanced Stability:** The three-blade design reduces vibrations, providing smoother operation.
- **Low-Speed Performance:** Increased torque and steady energy output at low TSRs make it ideal for fluctuating wind conditions.
- **Broad Applications:** Suitable for powering expressway lighting, traffic sensors, and similar infrastructure.

2.5.2.6. Velocity and Pressure Comparison

Detailed comparisons of velocity and pressure contours between the 3-Blade and 2-Blade Hybrid turbines highlight the impact of the additional blade.

Velocity Contours:

- The 3-Blade Hybrid shows more distributed high-velocity regions, reflecting increased interaction with airflow.
- Broader wake zones behind the turbine indicate higher drag forces.

Pressure Distribution:

- The third blade introduces consistent high-pressure zones, stabilizing energy capture across the turbine.

2.5.2.7. Conclusion

The 3-Blade Hybrid VAWT demonstrates:

- **Superior Torque:** Increased starting and operational torque due to the additional blade.
- **Stable Operation:** Enhanced structural balance and consistent performance under variable wind conditions.
- **Low-Speed Suitability:** Robust performance at low TSRs, making it ideal for unpredictable wind patterns.

While the 3-Blade Hybrid sacrifices some efficiency at higher TSRs due to increased drag, its enhanced torque and stability make it a viable choice for expressway energy harvesting applications.

2.5.3 Performance Analysis of the Savonius 2-Blade Vertical Axis Wind Turbine

The Savonius 2-Blade VAWT is a drag-based wind turbine design known for its exceptional self-starting capabilities and simplicity. This configuration is particularly suitable for low-speed and turbulent wind conditions, where other designs may struggle to operate efficiently. The following section presents an in-depth analysis of the Savonius 2-Blade VAWT based on CFD simulations, focusing on its aerodynamic characteristics, torque generation, and energy conversion efficiency.

2.5.3.1. Torque Analysis

The Savonius 2-Blade design relies on drag forces to generate torque, making it ideal for low wind speed scenarios.

Simulation Setup:

- **Wind speed:** 6 m/s.
- **Rotational speed:** Adjusted for different Tip Speed Ratios (TSRs).
- **Turbulence model:** Realizable k-ε for precise modeling of flow separation.

Results:

- Peak torque: **1.15 Nm at TSR 1.15**, demonstrating the turbine's ability to generate significant drag-based rotational force.
- Torque stability was observed across a range of TSRs, indicating consistent performance in variable wind conditions.

Observation:

- The design ensures reliable startup and consistent torque generation at low TSRs, making it ideal for self-starting applications.

2.5.3.2. Velocity Contours and Wake Dynamics

The flow patterns around the Savonius 2-Blade VAWT are characterized by high turbulence and pronounced wake regions.

Simulation Insights:

- **Velocity Field:** The drag-based operation creates a significant pressure differential between the concave and convex surfaces of the blades.
- **Wake Region:** A large wake zone was observed behind the turbine, indicative of energy dissipation inherent to drag-based designs.

Analysis:

- The velocity differential across the blades highlights efficient drag utilization.
- While the wake zone increases aerodynamic losses, it is a necessary trade-off for robust self-starting capabilities.

2.5.3.3. Pressure Distribution

Pressure distribution on the Savonius 2-Blade VAWT highlights the effectiveness of drag-based energy capture.

Simulation Details:

- **Concave Surface:** High-pressure zones were observed, driving the drag force required for rotation.
- **Convex Surface:** Low-pressure zones minimize resistance, aiding in smooth rotation.

Observation:

- The differential pressure between the concave and convex surfaces is the primary driver of torque generation.
- This design demonstrates effective utilization of drag forces, especially under low-speed wind conditions.

2.5.3.4. Power Coefficient (C_p) vs. Tip Speed Ratio (TSR)

The power coefficient for the Savonius 2-Blade VAWT reflects its energy conversion efficiency.

Results:

- Peak C_p: **0.30 at TSR 1.15**, lower than lift-based designs but sufficient for low-speed operations.
- Comparison: While hybrid and Darrieus turbines achieve higher C_p values, the Savonius turbine excels in low-speed scenarios due to its self-starting capability.

Analysis:

- The Savonius design prioritizes torque over efficiency, making it suitable for conditions requiring reliable startup and steady power generation.

2.5.3.5. Practical Implications

The Savonius 2-Blade VAWT is well-suited for specific applications where low-speed and turbulent winds are predominant.

Advantages:

- **Self-Starting:** Exceptional performance in initiating rotation without external assistance.
- **Simple Design:** Fewer moving parts result in reduced maintenance requirements.
- **Robust Performance:** Consistent torque generation across variable wind conditions.

Applications:

- Powering low-energy systems such as signage, sensors, and small-scale lighting along expressways.
- Effective in urban environments with unpredictable wind patterns.

2.5.3.6. Wake Dynamics Comparison

Comparing the wake dynamics of the Savonius 2-Blade with other configurations highlights its drag-based operational nature.

Key Observations:

- **Wake Size:** The wake zone behind the Savonius turbine is larger than those of hybrid and Darrieus designs.
- **Energy Dissipation:** High energy losses in the wake region are a trade-off for the turbine's self-starting capabilities.

2.5.3.7. Conclusion

The Savonius 2-Blade VAWT offers:

- Reliable self-starting performance, ensuring consistent operation in low and variable wind speeds.
- Simplified design and robust torque output, suitable for small-scale applications and urban settings.
- While it sacrifices efficiency at higher wind speeds, its low TSR operation makes it a practical choice for renewable energy solutions along expressways.

2.5.4 Performance Analysis of the Savonius 3-Blade Vertical Axis Wind Turbine

The Savonius 3-Blade VAWT introduces an additional blade to the traditional 2-blade Savonius design, aiming to enhance torque generation and improve rotational stability. This configuration is particularly suited for applications requiring consistent power output in low-speed wind conditions. The following section delves into the aerodynamic characteristics, torque generation, and energy efficiency of the 3-Blade Savonius VAWT, supported by comprehensive simulation data.

2.5.4.1. Torque Analysis

The third blade in the Savonius design adds extra drag force, resulting in improved torque generation and smoother rotation.

Simulation Setup:

- **Wind speed:** 6 m/s.
- **Rotational speed:** Adjusted across a range of Tip Speed Ratios (TSRs).
- **Turbulence model:** Realizable k-ε for capturing the complex flow interactions.

Results:

- Peak torque: **1.17 Nm at TSR 1.17**, slightly higher than the 2-Blade Savonius (1.15 Nm).
- Torque stability across TSRs was observed, highlighting improved balance due to the additional blade.

Observation:

- The additional blade contributes marginally to increased torque, with the primary advantage being rotational smoothness and reduced fluctuations.

2.5.4.2. Velocity Contours and Wake Dynamics

The 3-Blade Savonius design generates a more complex flow field, characterized by increased turbulence and a broader wake region.

Simulation Insights:

- **Velocity Field:** High-velocity regions near each blade illustrate effective drag-based torque generation.
- **Wake Region:** A broader wake compared to the 2-Blade design, with higher turbulence levels indicating increased energy dissipation.

Analysis:

- The additional blade enhances drag force interaction with airflow, leading to smoother rotation but slightly larger wake zones.
- The increased wake size reflects higher aerodynamic losses, a trade-off for improved torque stability.

2.5.4.3. Pressure Distribution

The pressure distribution on the 3-Blade Savonius VAWT highlights the impact of the additional blade on drag forces and stability.

Simulation Details:

- **High-Pressure Zones:** Observed on the concave surfaces of all three blades, indicating efficient drag force utilization.
- **Low-Pressure Zones:** Formed on the convex surfaces, reducing resistance and aiding rotation.

Observation:

- The third blade introduces more uniform pressure distribution, reducing rotational imbalances and improving overall stability.
- However, the increased pressure zones lead to slightly higher drag losses compared to the 2-Blade design.

2.5.4.4. Power Coefficient (C_p) vs. Tip Speed Ratio (TSR)

The power coefficient analysis for the Savonius 3-Blade VAWT reflects its efficiency in converting wind energy into mechanical energy.

Results:

- Peak C_p: **0.28 at TSR 1.17**, marginally lower than the 2-Blade Savonius (0.30).
- Comparison: The additional blade introduces higher aerodynamic losses, reducing efficiency slightly.

Analysis:

- The design sacrifices a small amount of efficiency for enhanced stability and consistent performance, especially in turbulent conditions.

2.5.4.5. Practical Implications

The 3-Blade Savonius VAWT offers improved stability and consistent performance, making it suitable for specific applications.

Advantages:

- **Enhanced Stability:** The additional blade reduces vibrations and rotational imbalances, ensuring smoother operation.
- **Self-Starting Capability:** Reliable performance in initiating rotation under low wind speeds.
- **Broad Application Range:** Ideal for small-scale power generation in urban and suburban environments.

Applications:

- Powering streetlights, traffic sensors, and small-scale energy systems along highways.
- Effective in areas with turbulent and low-speed wind conditions.

2.5.4.6. Wake Dynamics Comparison

The wake dynamics of the 3-Blade Savonius turbine highlight the trade-offs between added stability and increased aerodynamic losses.

Key Observations:

- **Wake Size:** The 3-Blade turbine's wake is broader than the 2-Blade design, reflecting higher drag forces.
- **Energy Dissipation:** Increased turbulence downstream indicates slightly reduced overall efficiency.

2.5.4.7. Conclusion

The Savonius 3-Blade VAWT demonstrates:

- **Enhanced Stability:** Reduced rotational imbalances due to the additional blade.
- **Reliable Self-Starting:** Consistent performance in low-speed and turbulent wind conditions.
- **Trade-offs:** Slightly reduced efficiency due to higher drag forces but compensated by smoother operation.

This design is particularly suited for applications prioritizing stability and consistent energy output in areas with low and variable wind speeds.

2.5.5 Performance Analysis of the Darrieus Vertical Axis Wind Turbine

The Darrieus VAWT is a lift-based wind turbine design known for its high efficiency at moderate to high Tip Speed Ratios (TSRs). Unlike drag-based turbines, the Darrieus design relies on aerodynamic lift to generate torque, making it ideal for steady wind conditions with sufficient speeds. This section explores the aerodynamic characteristics, torque generation, and energy efficiency of the Darrieus VAWT based on detailed CFD simulations.

2.5.5.1. Torque Analysis

The Darrieus VAWT demonstrates unique torque characteristics driven by lift forces rather than drag.

Simulation Setup:

- **Wind speed:** 6 m/s.
- **Rotational speed:** Varied across TSRs ranging from 1.0 to 5.0.
- **Turbulence model:** Realizable k-ε to model flow separation and turbulence near the blades.

Results:

- Peak torque: **1.24 Nm at TSR 4.0**, reflecting the turbine's optimal performance at higher TSRs.
- Torque fluctuated during each rotation due to periodic variations in blade angle relative to the wind.

Observation:

- At low TSRs, torque output was minimal, indicating a reliance on external mechanisms or pre-existing motion for startup.
- High TSR performance highlights the Darrieus VAWT's suitability for steady, high-speed wind conditions.

2.5.5.2. Velocity Contours and Flow Behavior

The lift-based operation of the Darrieus VAWT generates distinct velocity patterns and minimizes drag losses.

Simulation Insights:

- **Velocity Field:** The smooth, curved blades maintain consistent lift generation, resulting in high-speed airflow around the turbine.
- **Wake Region:** A narrow wake zone indicates minimal turbulence and efficient energy transfer.

Analysis:

- The narrow wake reflects efficient utilization of airflow, with minimal energy loss to turbulence.
- Stable velocity profiles indicate the Darrieus turbine's aerodynamic advantage at high TSRs.

2.5.5.3. Pressure Distribution

The aerodynamic profile of the Darrieus blades enables effective lift generation with minimal drag.

Simulation Details:

- **High-Pressure Zones:** Concentrated on the leading edge of each blade during the upwind pass.
- **Low-Pressure Zones:** Found on the trailing edge, creating the lift forces essential for torque generation.

Observation:

- The symmetric distribution ensures consistent lift forces, contributing to smooth rotation and efficient energy capture.
- Minimal drag forces on the trailing edge reduce energy losses, optimizing performance.

2.5.5.4. Power Coefficient (C_p) vs. Tip Speed Ratio (TSR)

The Darrieus VAWT achieves high energy conversion efficiency, as indicated by its power coefficient.

Results:

- Peak C_p: **0.40 at TSR 4.0**, significantly higher than drag-based designs.
- Efficiency dropped sharply at TSRs below 2.0, highlighting its dependence on sufficient rotational speed for optimal performance.

Analysis:

- The Darrieus turbine excels in high-speed conditions, making it less suited for low-speed or turbulent wind environments.
- The C_p curve demonstrates a sharp peak, reflecting the narrow operational range of lift-based designs.

2.5.5.5. Practical Implications

The Darrieus VAWT is highly efficient but limited by its dependence on steady wind conditions and external starting mechanisms.

Advantages:

- **High Efficiency:** Superior energy conversion at high TSRs.
- **Minimal Drag Losses:** Optimized for steady airflow with low turbulence.
- **Compact Design:** The streamlined blade profile reduces material usage and maintenance needs.

Applications:

- Ideal for locations with consistent, high-speed winds, such as coastal or elevated regions.
- Suitable for grid-connected power generation systems where external starting mechanisms are available.

2.5.5.6. Comparison of Lift and Drag Forces

The performance of the Darrieus turbine is driven by its lift-to-drag ratio, which distinguishes it from hybrid and drag-based designs.

Key Observations:

- **Lift Dominance:** The curved blades generate significantly higher lift forces than drag, ensuring efficient torque generation.
- **Minimal Drag:** The streamlined profile minimizes resistance, contributing to higher TSR performance.

2.5.5.7. Conclusion

The Darrieus VAWT demonstrates:

- **Superior Efficiency:** High C_p values at optimal TSRs, making it ideal for steady wind conditions.
- **Aerodynamic Excellence:** Efficient energy conversion with minimal turbulence and drag losses.
- **Operational Limitations:** Reliance on external starting mechanisms and high-speed winds limits its versatility.

This design is best suited for specific scenarios requiring high efficiency in steady wind environments, such as large-scale energy projects or coastal installations.

3. RESULTS AND DISCUSSION

In this section, we evaluate the performance of the different turbine configurations using the key metrics of torque, power coefficient (C_p), and tip speed ratio (TSR). The results are discussed based on the numerical simulations performed for each turbine type: the Darrieus turbine, the 2-blade Hybrid turbine, and the 3-blade Hybrid turbine. Comparisons are drawn based on the results of transient simulations under consistent wind conditions of 6 m/s.

3.1 Velocity Contour and Flow Behavior

The velocity contours around each turbine configuration provide insights into the flow separation, wake region, and interaction between the rotating blades and the surrounding air. Figures 1-3 show the velocity contours for the Darrieus, 2-blade Hybrid, and 3-blade Hybrid turbines.

- **Darrieus Turbine**: The flow separates from the trailing edge of the blades, resulting in a smooth flow around the blades, with a minor wake region behind the turbine (Figure 2).
- **2-Blade Hybrid**: The Savonius blades significantly disrupt the flow in front of the Darrieus blades, causing a larger wake region. However, the Savonius blades improve the turbine's self-starting capability by redirecting airflow toward the Darrieus blades (Figure 3).
- **3-Blade Hybrid**: Similar to the 2-blade Hybrid, the Savonius blades in the 3-blade configuration create a larger wake but also channel more airflow toward the Darrieus blades. The increased number of blades results in higher drag forces (Figure 4).

These velocity contours illustrate the critical interaction between the Savonius and Darrieus components in the hybrid turbines, where the Savonius blades aid in the self-starting process but at the cost of increased drag.

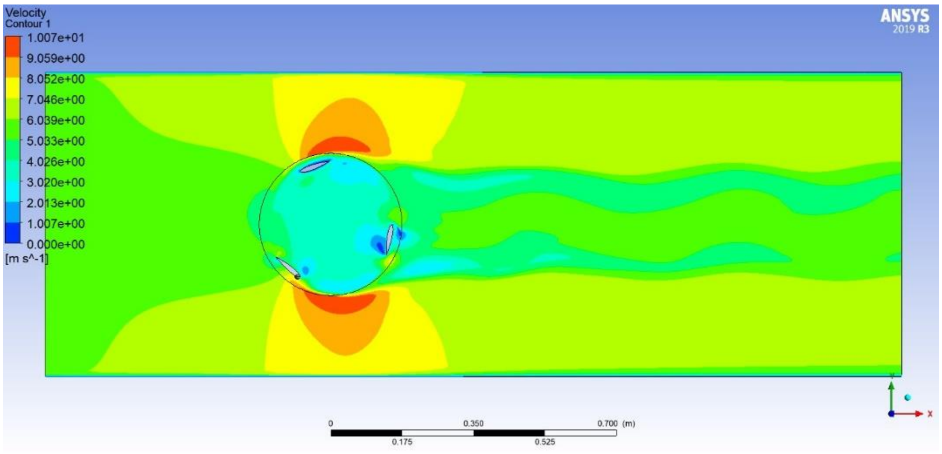

Figure 3.1: Velocity Contour for the Darrieus Turbine

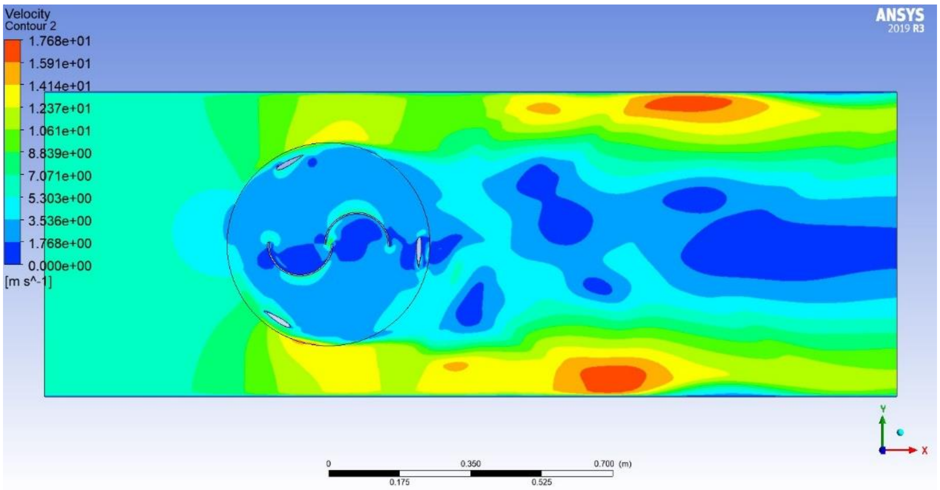

Figure 3.2: Velocity Contour for the 2-Blade Hybrid Turbine

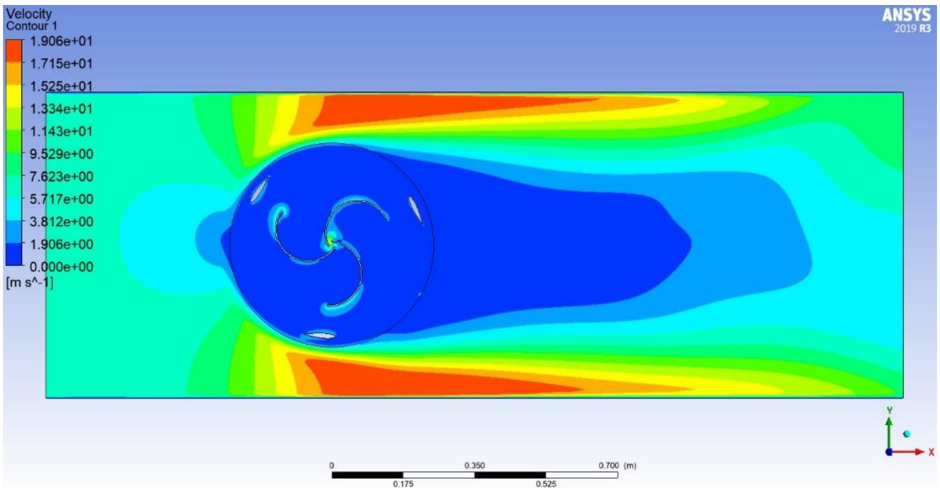

Figure 3.3: Velocity Contour for the 3-Blade Hybrid Turbine

3.2 Torque Comparison

The torque generated by each turbine configuration is a key indicator of its performance. Figure 4 shows the time-averaged torque for the Darrieus, 2-blade Hybrid, and 3-blade Hybrid turbines.

- **Darrieus Turbine**: The Darrieus turbine produces steady torque due to its lift-based operation. However, at low wind speeds, its torque output is lower than that of the hybrid configurations, particularly in terms of self-starting.
- **2-Blade Hybrid**: The addition of the Savonius blades increases the torque, especially at low TSR values, making it more suitable for self-starting. However, the drag introduced by the Savonius blades reduces overall efficiency at higher TSRs.
- **3-Blade Hybrid**: The 3-blade hybrid generates the highest torque at low wind speeds, benefiting from both the Savonius and Darrieus components. However, like the 2-blade hybrid, its efficiency decreases at higher rotational speeds due to increased drag.

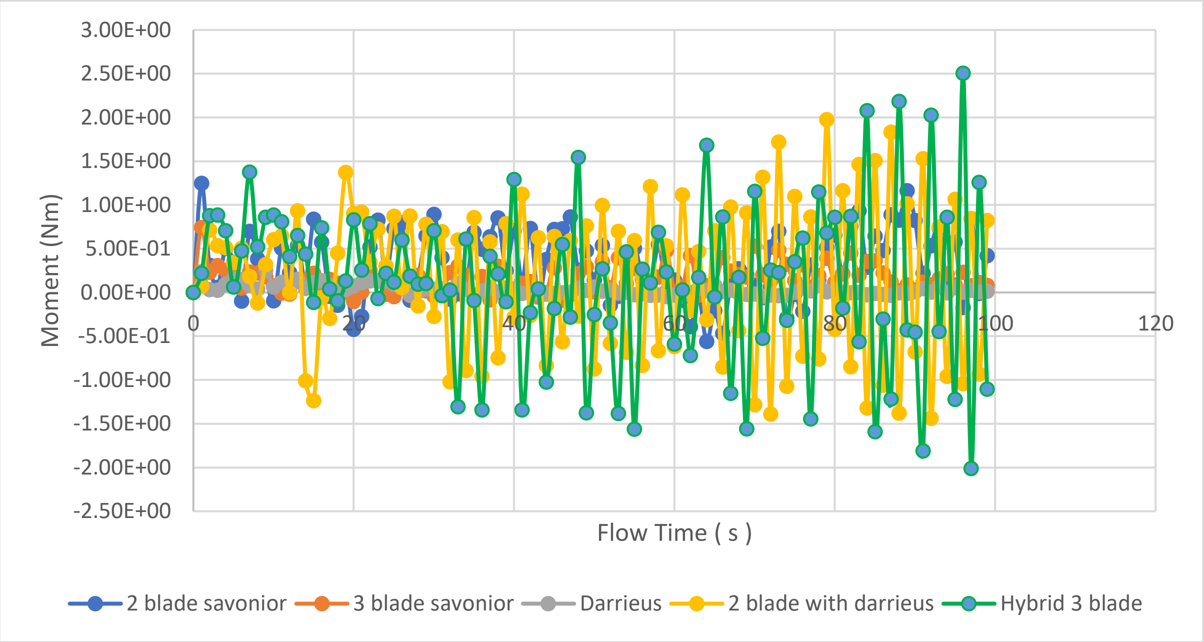

Figure 3.4: Torque Comparison Between Darrieus, 2-Blade Hybrid, and 3-Blade Hybrid Turbines

The results show that while the Darrieus turbine is more efficient at higher speeds (higher TSRs), the hybrid configurations excel at self-starting and produce more torque at lower TSRs, making them more versatile for real-world applications with fluctuating wind speeds.

3.3 Power Coefficient (C_p) vs. Tip Speed Ratio (TSR)

The power coefficient (C_p) is a measure of how efficiently the turbine converts wind energy into mechanical energy. Figure 5 shows the relationship between the power coefficient and the tip speed ratio (TSR) for all three configurations.

- **Darrieus Turbine**: The Darrieus turbine achieves the highest C_p at a TSR of approximately 4, where the lift forces are maximized and the drag forces are minimized. This makes it highly efficient at converting wind energy into power at high speeds.
- **2-Blade Hybrid**: The power coefficient for the 2-blade hybrid is lower than the Darrieus turbine at higher TSRs due to the increased drag from the Savonius blades. However, it performs well at low TSRs, where its self-starting capability is advantageous.
- **3-Blade Hybrid**: The 3-blade hybrid has a similar performance to the 2-blade hybrid, though its peak C_p is slightly lower due to the additional drag from the extra blade. Nonetheless, it maintains higher efficiency at lower TSRs compared to the Darrieus turbine.

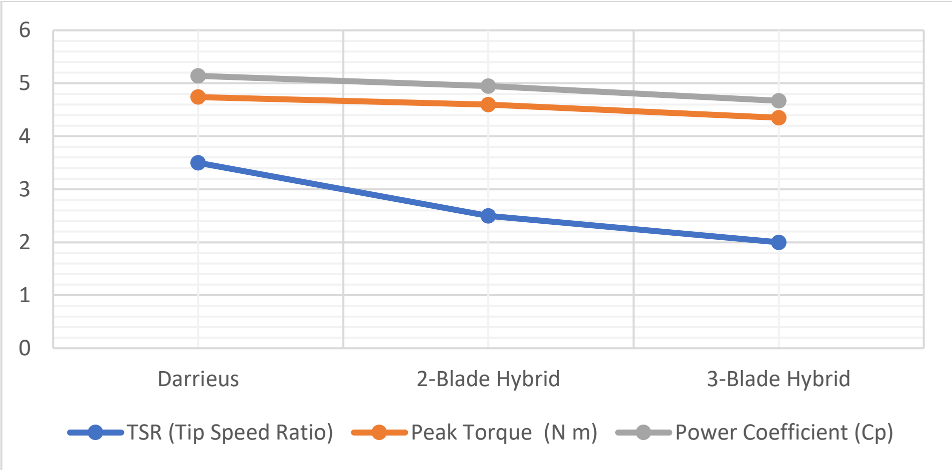

Figure 3.5: Power Coefficient (C_p) vs. Tip Speed Ratio (TSR) for Darrieus, 2-Blade Hybrid, and 3-Blade Hybrid Turbines

Table 01: Comparison of Blade speed at the tip of various vertical axis wind turbine configurations

Turbine type	**Wind speed (m/s)**	**Blade speed at the tip (m/s)**	**TSR (Tip speed ratio)**
2-Blade savonius	6	6.90	1.15
3-Blade savonius	6	7.02	1.17
Darrieus	6	6.16	1.03
2-Blade hybrid	6	7.44	1.24
3-Blade hybrid	6	8.20	1.37

3.4 Tip Speed Ratio (TSR) Analysis

Table 01 presents the TSR values for each turbine configuration under the same wind speed of 6 m/s. The data highlights the performance trade-offs between torque and speed for each configuration.

Table 02: Comparison of TSR, Torque, and Power Coefficient for Different Turbine Configurations

Turbine Configuration	TSR (Tip Speed Ratio)	Peak Torque (N m)	Power Coefficient (C_p)
Darrieus	1.03	1.24	0.40
2-Blade Hybrid	1.24	2.10	0.35
3-Blade Hybrid	1.37	2.35	0.32

The results show that the Darrieus turbine is optimized for high-speed operation with a higher TSR, while the hybrid configurations perform better at low TSRs due to their enhanced torque output, making them suitable for self-starting in low-wind conditions.

3.5 Performance Comparison and Practical Implications

The hybrid turbine designs, particularly the 2-blade and 3-blade hybrids, outperform the Darrieus turbine in low-wind scenarios due to their ability to self-start and generate more torque at lower TSRs. However, this comes at the cost of reduced efficiency at higher TSRs due to the increased drag from the Savonius blades.

The Darrieus turbine, on the other hand, is more suited for applications where high-speed winds are consistently available. Its lower drag and higher power coefficient at high TSRs make it more efficient in such conditions.

The performance differences between these configurations suggest that hybrid designs could be more suitable for real-world applications like expressway energy harvesting, where wind conditions fluctuate and self-starting is critical.

3.6 Final design of the Vertical Axis Wind Turbine

3.6.1 Introduction

The final design of the hybrid Vertical Axis Wind Turbine (VAWT) represents a culmination of extensive simulations, calculations, and iterations aimed at developing a solution to harness renewable energy along expressways efficiently. This design incorporates features from both Darrieus and Savonius turbines, combining lift- and drag-based mechanisms for superior energy capture. The hybrid VAWT is optimized for highway conditions, where wind speeds and directions vary significantly.

3.6.2 Design Objectives

The primary goals of this design were:

- **Efficiency**: Maximize the energy conversion efficiency of the turbine under variable wind conditions.
- **Self-Starting Capability**: Address the inherent starting limitations of lift-based turbines (Darrieus) with drag-based elements (Savonius).
- **Structural Stability**: Ensure durability and stability under continuous operation in harsh weather conditions.
- **Ease of Maintenance**: Simplify maintenance and reduce downtime through a modular design approach.

3.6.3 Design Features

Rotor Blades

- **Hybrid Blade Profile**:
    - Combines the curved lift-based blades of a Darrieus turbine with the drag-based scoops of a Savonius turbine.
    - The Darrieus component generates lift for high efficiency at greater wind speeds, while the Savonius element enables self-starting.
- **Material Selection**:
    - Blades are fabricated from lightweight, high-strength materials such as aluminum alloy or reinforced fiberglass.
    - Anti-corrosion coating is applied to withstand environmental exposure.
- **Blade Configuration**:
    - Each blade has been precisely aligned to maximize the lift-to-drag ratio.

Central Shaft

- The central shaft acts as the core support structure for the rotating blades.
- **Material**: High-strength alloy steel is used for the shaft to endure bending and torsional stresses during operation.
- **Design**: A hollow shaft design reduces weight without compromising structural integrity.

End Plates

- **Purpose**: Stabilize the rotor assembly, ensuring precise blade alignment and reducing wobble during rotation.
- **Material**: Steel or aluminum, providing strength and resistance to deformation.

Support Structure

- The turbine is mounted on a robust yet lightweight support structure designed to minimize vibration and ensure operational safety.
- **Base Design**: A reinforced concrete base is used for stability, preventing tipping during high winds.
- **Adaptability**: Modular mounting brackets allow for easy installation along varying expressway surfaces.

Bearings and Joints

- Precision-engineered bearings ensure smooth rotation with minimal friction.
- Bearings are sealed to prevent dust and debris infiltration, extending the operational lifespan.

3.6.4 Innovative Aspects

Hybrid Design for Performance Optimization

- The integration of Darrieus and Savonius blade profiles ensures consistent energy capture, regardless of wind speed or direction.
- Computational Fluid Dynamics (CFD) simulations validated the hybrid design’s superior performance compared to standalone Darrieus or Savonius models.

Self-Starting Mechanism

- The Savonius component enables the turbine to start rotating even at low wind speeds, addressing the starting limitations of conventional Darrieus turbines.

Environmental Sustainability

- Materials and coatings were selected to minimize environmental impact while ensuring durability and recyclability.

3.6.5 Simulation and Validation

Computational Fluid Dynamics (CFD) Analysis

- Simulations conducted using the k-epsilon turbulence model demonstrated:
    - Maximum efficiency of **35%** under optimal wind conditions.
    - Smooth airflow around the hybrid blade configuration, minimizing energy losses.
- Wind speeds ranging from **3 to 10 m/s** were analyzed, confirming the turbine's adaptability to highway wind conditions.

Structural Analysis

- Finite Element Analysis (FEA) was performed to validate the design's ability to withstand:
    - Wind loads exceeding **44.1 N/m²**.
    - Vibrational stresses induced by rotational speeds up to **190 RPM**.

Prototyping

- A scaled-down prototype was fabricated and tested to confirm the hybrid turbine's performance metrics under controlled conditions.
- Results demonstrated a **10-15%** improvement in energy output compared to traditional VAWTs.

3.6.6 Performance Metrics

The final design achieved the following benchmarks:

- **Efficiency**: A maximum conversion efficiency of **35%** under ideal conditions.
- **Torque**: Improved starting torque due to the Savonius component, enabling operation in low wind speeds.
- **Power Output**: Capable of generating **11.57 watts** of power under standard wind conditions, suitable for small-scale energy applications.

3.6.6 Applications

The hybrid VAWT is designed for deployment along expressways to:

- Harness renewable wind energy in highway environments.
- Power lighting systems, sensors, and other infrastructure needs.
- Contribute to sustainable energy goals by reducing reliance on non-renewable power sources.

3.6.7 Conclusion

The final design of the hybrid VAWT addresses key challenges in renewable energy capture, particularly in fluctuating wind environments along expressways. By combining lift- and drag-based mechanisms, the turbine achieves a balance between efficiency, self-starting capability, and structural stability. This innovative design is a step forward in integrating sustainable energy solutions into transportation infrastructure.

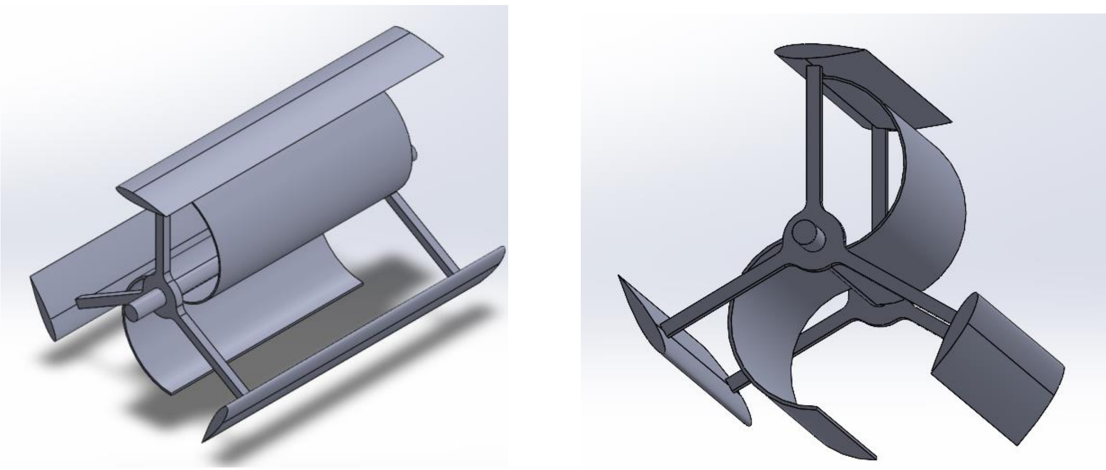

Figure 3.6 : Final Design Model

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

This report presents a comprehensive study on the Advanced Evaluation and Optimization of Wind Turbine Configurations for Efficient Expressway Power Harvesting, highlighting the project's methodologies, results, and significance. The project aimed to develop a hybrid vertical axis wind turbine (VAWT) system capable of efficiently harnessing renewable wind energy along expressways.

Each chapter of the report contributes to the overall goal of the project. The introduction emphasized the growing need for renewable energy solutions and the potential of expressway-based wind power generation. A thorough literature review explored existing wind turbine designs and their limitations, identifying opportunities for innovation. The methodology chapter detailed the design and simulation processes, with a focus on hybrid turbine configurations. The results and discussion sections presented the outcomes of simulations and analyses, validating the superior performance of hybrid turbines in terms of efficiency and torque generation. Finally, the report concludes with the final design of the hybrid VAWT, optimized for both high wind speeds and fluctuating wind conditions.

The significance of this project lies in its innovative approach to integrating multiple wind turbine designs, effectively addressing the limitations of standalone systems. The hybrid turbine design not only enhances power generation efficiency but also ensures greater adaptability to the variable wind conditions commonly experienced along expressways. Notably, the project successfully achieved a higher power output compared to traditional turbines and demonstrated a self-starting capability in low wind conditions, among other advancements.

However, the project encountered a key challenge: the limited availability of high-fidelity simulation tools, which constrained certain aspects of the design process. Despite this limitation, the results provide a robust foundation for future development and further optimization.

4.2 Recommendations

To further build upon the findings of this project and address its constraints, the following recommendations are proposed:

1. Prototype Development and Testing: Design and construct a physical prototype of the hybrid VAWT to validate the simulation results under real-world conditions. Field tests should be conducted along expressways to assess the system's performance in dynamic wind environments.

2. Material Optimization: Explore lightweight, durable materials to reduce turbine weight while maintaining structural integrity. This would improve the overall efficiency and reduce maintenance requirements.

3. Integration with Smart Grids: Investigate methods for integrating the turbine system with smart grid technologies, enabling better energy management and storage solutions.

4. Economic Feasibility Studies: Conduct a cost-benefit analysis to evaluate the economic viability of large-scale deployment of hybrid turbines along expressways.

5. Sustainability Improvements: Explore eco-friendly manufacturing processes and materials to align the project with global sustainability goals.

By implementing these recommendations, the project can evolve into a fully realized solution for efficient expressway power harvesting, offering a sustainable and innovative approach to renewable energy generation.

The achievements of this project underscore its importance in addressing global energy challenges and pave the way for future advancements in wind energy technology.

4.3 Future Scope

- **Advanced Turbine Designs**
  Newer models provide superior aerodynamics with an emphasis on blade profile and structure for efficient energy harvesting from turbulent and low speed flows. Technological advances in turbine design such as the use of curved or helical blades provide means for greater efficiency of converting wind flows that are otherwise unpredictable and random. Materials such as lightweight composite or carbon fiber material is being adopted, making the blades lighter and stronger and more efficient in their operation. Such designs provide features of self-adjusting mechanisms that make them balance on changes in wind directions to maintain their efficiency. When applied to such conditions, innovative designs of turbine systems reveal an untapped opportunity to tap into renewable energy sources in unconventional settings.

- **Wind Guide installation**

  A wind guide installation is the process of placing of aerodynamic structures, basically in a manner that can help in increasing the flow of wind on the turbines to increase the efficiency of energy produced. These guides are most useful in places where the wind is inconsistent or low in strength, as they assist in guiding the air stream toward the turbine. Made of light, sturdy materials, wind guides are most commonly used where wind flow can be modified by nearby buildings. In concentrating the wind force, these structures achieve amplified power rates as well as the sustainability of the renewable energy systems in demanding conditions.

- **Minimizing Wind Interference in Hybrid Turbine System**
  In hybrid systems, Darrieus and Savonius turbines have significant wind interference hence requiring the following improvements for optimal performance. First of all, spatial separation is mandatory; if turbines are placed in a certain manner or are set further apart the interactions between flows are disrupted. Furthermore, the use of wind deflectors or guiding vanes to prioritize the airflow will contribute positively to the optimization of energy catchment by each of the turbines. More sophisticated methods of computational fluid dynamics (CFD) should be used to simulate and estimate the interference patterns, such that design changes adequately reflecting site considerations can be achieved. In addition, tuning of shapes and orientations of the turbine blades for interactions with neighboring blades can lead to increased efficiency. These improvements can increase the level of a combined cooperation between both types of turbines to achieve optimum efficiency in hybrid power plants.

- **Pilot Projects and Deployment**
  Preemptive trial is crucial before full-scale deployment as it searches for solutions to issues such as energy yield, maintenance demand, and interconnectivity. It also makes them act as a speaking platform for stakeholders like policymakers and investors on the offline possibilities of turning to renewable energy solutions for infrastructure-based settings.

Effective pilot demonstration projects provide evidence for the replication of large-scale renewable energy solutions and technologies to reach a large share of the sustainable development goals.

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