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# Design and Development of a Small-Scale Composite Vertical-Axis Wind Turbine

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A B S T R A C T

Pakistan faces persistent energy shortages, largely due to its heavy reliance on fossil fuels, which leads to environmental degradation and economic constraints. This work presents the design, fabrication, and testing of a small-scale, low-cost vertical-axis wind turbine (VAWT) suitable for both urban and rural installations. The turbine utilizes a H-Darrieus configuration with three blades, employing a NACA 0021 symmetric airfoil, which is optimized for operation at low wind speeds. Blades were manufactured using glass fiber-reinforced plastics (GFRP) with a pharma core, achieving a high stiffness-to-weight ratio. An axial flux generator with a double-rotor, single-stator design was integrated for electrical generation. Designed for a wind speed of 8 m/s, the turbine achieved a torque of 14.5 Nm and mechanical power output of 257 W, corresponding to a power coefficient of 0.40. Accounting for generator efficiency (90%), the effective coefficient of performance was 0.36. Mechanical testing validated the structural integrity of the composite blades, while experimental runs confirmed reliable performance across varying wind speeds and angles of attack. The complete prototype cost approximately PKR 30,000 and weighed 20.3 kg, demonstrating the feasibility of localized, small-scale wind energy solutions for Pakistan.

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# INTRODUCTION

## Motivation

Pakistan is experiencing a persistent energy crisis, primarily caused by its heavy dependence on fossil fuels for over 60% of total energy production. This dependence contributes significantly to environmental degradation, including global warming and air pollution, while also placing an economic burden due to high costs of fuel imports. The national energy demand stands at approximately 20,000 MW per day, yet production falls short by 5,000–9,000 MW daily. Renewable energy sources such as solar, thermal, biomass, and wind offer sustainable alternatives that can help bridge this gap. Among these, wind energy presents considerable untapped potential in Pakistan, estimated at around 300 GW.

However, large-scale wind energy projects require substantial capital investment, which can be challenging to secure for a developing economy. Small-scale solutions, such as Vertical-Axis Wind Turbines (VAWTs), present a viable option for localized energy generation. These systems can be installed in both urban and rural environments, including remote areas with limited or no grid access. Compared to Horizontal-Axis Wind Turbines (HAWTs), VAWTs are mechanically simpler, operate in variable wind directions without the need for yaw mechanisms, and allow the generator and gearbox to be mounted at the base for easier maintenance.

Figure 1. VAWT

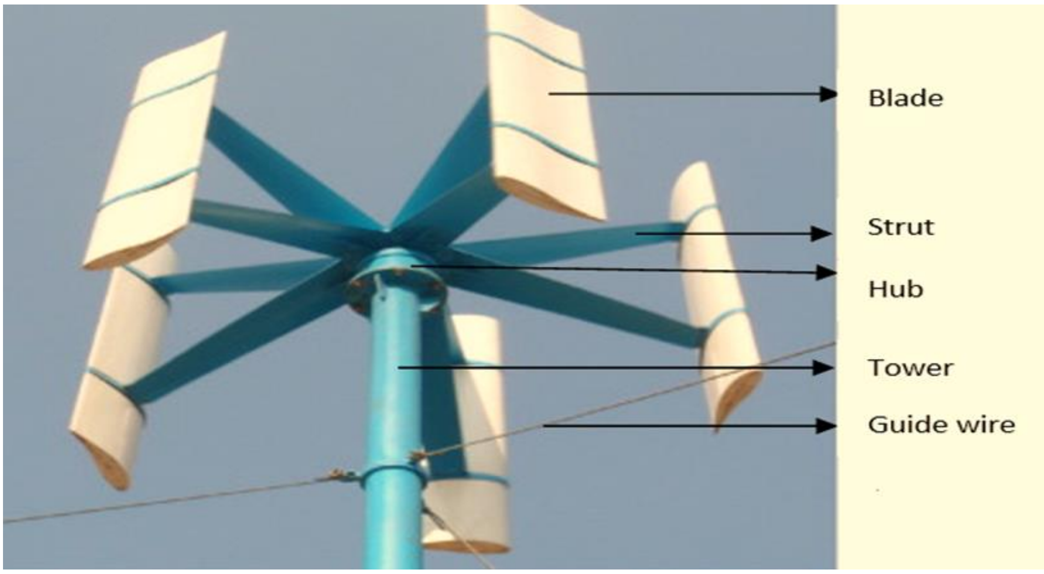


Figure 2. Turbine Parts

This research focuses on the design, fabrication, and performance evaluation of a small-scale composite VAWT optimized for low wind speeds. The design employs a three-blade H-Darrieus configuration with the NACA 0021 symmetric airfoil, chosen for its high thickness and self-starting capability. Lightweight composite construction using fiberglass reinforced plastics (GFRP) and thermocol ensures a high stiffness-to-weight ratio, while an axial flux generator provides efficient electrical output. The system was developed using locally available materials and low-cost manufacturing techniques, making it suitable for deployment in Pakistan's diverse geographic and economic settings.

## LITERATURE REVIEW

The growing global demand for energy, coupled with the depletion of fossil fuel resources, has accelerated the need for renewable energy solutions. Nearly 80% of the world's energy requirements are met through conventional natural resources, with renewable energy contributing only 13.1% and nuclear energy 6.5%. This imbalance has led policymakers to promote decentralized renewable energy systems for both domestic and industrial applications. In Pakistan, the energy crisis is severe, with many areas having limited or no access to electricity. The majority of the country's energy production comes from fossil fuels, while renewable sources such as wind remain underdeveloped due to infrastructure and investment limitations. The per capita energy demand is rising, creating a significant shortfall between supply and demand. Vertical-Axis Wind Turbines (VAWTs) have gained attention as a potential small-scale solution for localized power generation. They can be installed in remote and urban areas, are less sensitive to wind direction changes, and are mechanically simpler than Horizontal-Axis Wind Turbines (HAWTs). The location of the gearbox and generator at the base of the tower simplifies installation, operation, and maintenance, making VAWTs particularly suitable for rural electrification.

Previous studies have investigated various rotor designs, blade configurations, and aerodynamic optimizations to enhance VAWT performance. For small-scale systems, the use of self-starting airfoils such as NACA 0021 has been shown to improve performance at low wind speeds. Incorporating lightweight composite materials like fiber-reinforced plastics (FRPs) in blade construction reduces mass while maintaining mechanical strength, thereby improving turbine efficiency. In this research, a small-scale composite VAWT was designed, fabricated, and tested to meet localized energy demands. The system used a three-blade H-Darrieus configuration with NACA 0021 blades, a composite sandwich construction of fiberglass and thermocol, and an axial flux generator for electrical output. Experimental testing assessed performance under different wind velocities and blade angles of attack.

**Research Gaps and Contributions**

Although significant progress has been made in the development of small-scale vertical-axis wind turbines (VAWTs), certain limitations remain unaddressed. Current studies give limited focus to reducing mechanical friction through advanced bearing technologies and improving rotor balance and precision during fabrication, both essential for enhancing long-term stability. Similarly, there is insufficient exploration of cost-effective gearing mechanisms to improve energy capture under low wind speed conditions, where turbine performance usually declines. In addition, achieving uniformity in composite blade manufacturing and incorporating robust safety features, such as clutch and brake systems, to withstand extreme wind conditions, are areas that require further investigation. Bridging these gaps is crucial for advancing the efficiency, durability, and practical deployment of localized wind energy systems in Pakistan and similar regions. Key contributions of this research are the following:

1) This research presents the design, fabrication, and experimental validation of a cost-effective composite VAWT specifically optimized for Pakistan's low wind speed environment. The prototype achieved a power coefficient of 0.40 and an effective coefficient of 0.36, with a total cost of only PKR 30,000 and a weight of 20.3 kg. These outcomes demonstrate that affordable, locally manufactured wind turbines can provide reliable, small-scale renewable energy solutions, particularly for distributed generation in rural and urban communities.
2) The study also introduces a high-efficiency double-rotor, single-stator axial flux generator integrated into the VAWT design, achieving 90% efficiency through optimized air gap settings. By combining advanced generator design with lightweight composite blades, this work delivers a practical model for small-scale wind energy systems. The findings highlight a scalable and replicable solution for reducing fossil fuel dependence, lowering environmental impact, and strengthening energy security, thereby offering a meaningful contribution to Pakistan's renewable energy transition.

## METHODOLOGY

### Turbine Design

The small-scale Vertical-Axis Wind Turbine (VAWT) was designed using Pro-E (Creo) 3D modeling software. The aerodynamic design parameters were determined from established theoretical models and validated with prior research. A three-blade H-Darrieus configuration was selected to balance efficiency, stability, and structural simplicity, as seen in Figure 3.

The NACA 0021 airfoil profile was chosen due to its symmetrical shape, relatively high thickness, favorable lift-to-drag ratio at low Reynolds numbers, and self-starting capability, as shown in Figures 4 and 5. This profile operates effectively at low wind speeds and offers good structural stiffness when implemented in composite form.

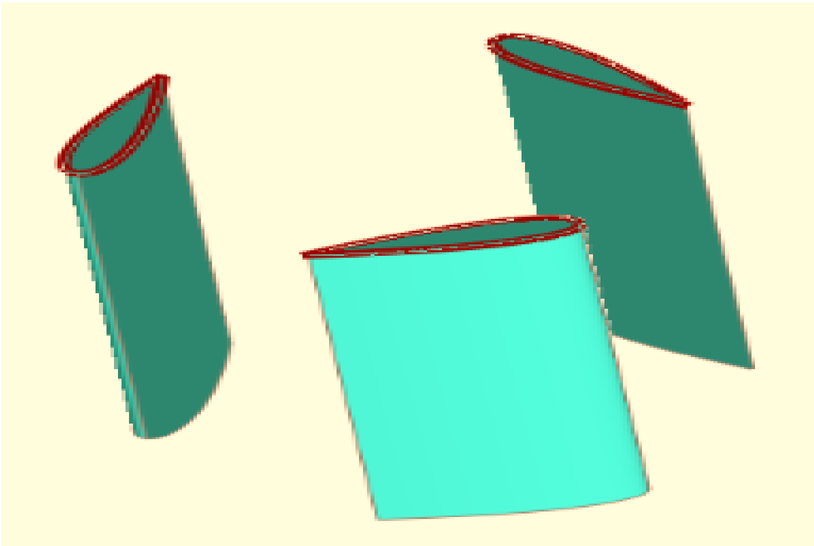

Figure 3. Model of Turbine Blades

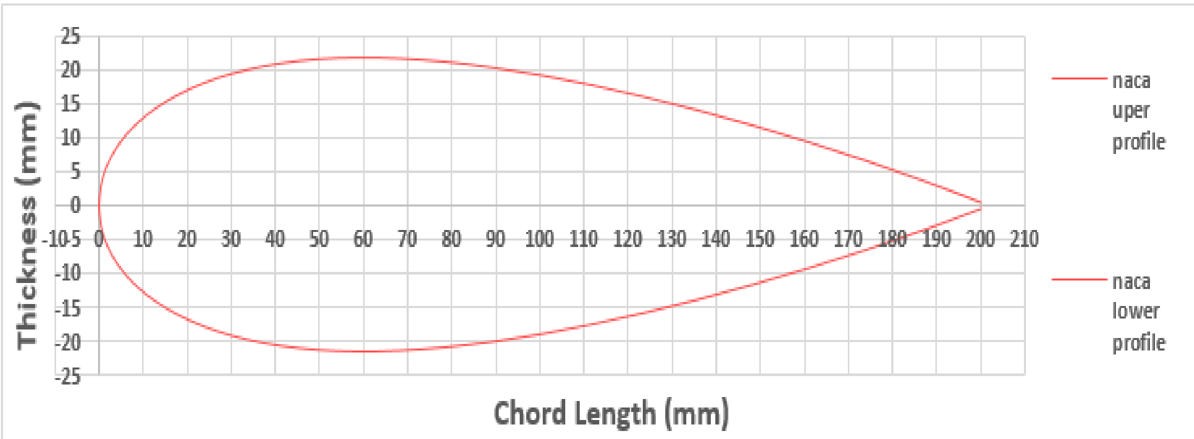


Figure 4. Airfoil NACA 0021

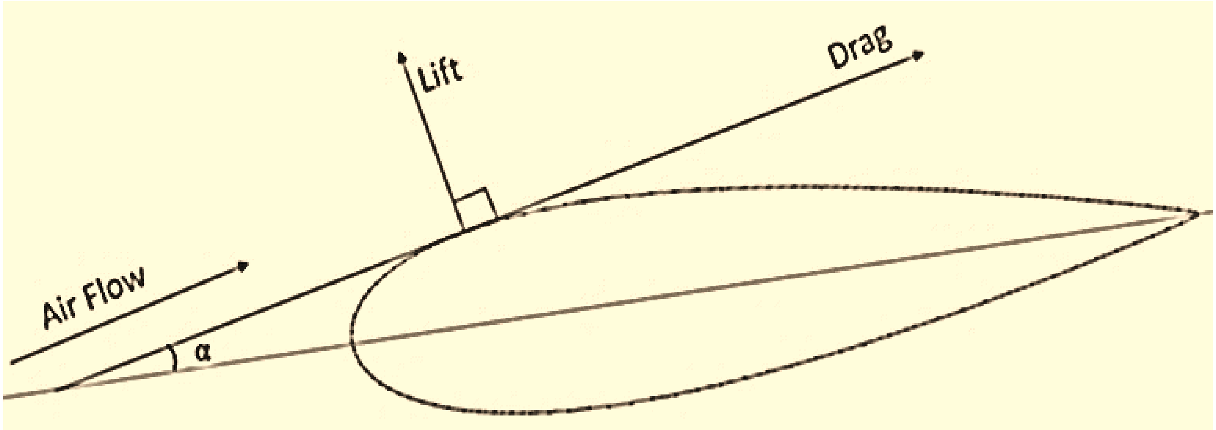


Figure 5. Airflow on the Airfoil

Table 1. Parametric Specifications of Turbine

| Parameter | Value | Parameter | Value | Parameter | Value |
|---|---|---|---|---|---|
| Turbine radius | 0.9m | Swept area | 2.07 m² | Torque | 14.5Nm |
| Blade length | 1.15m | Solidity | 0.67 | Rotor efficiency | 0.40 |
| Blade chord | 0.2m | Wind speed | 8m/s | Captured power | 257W |
| Tip speed ratio | 2 | Air density | 1.225 kg/m³ | Frictional losses | 6.8W |
| Number of blades | 3 | Voltage | 12V | Windage losses | 1.3W |
| Mechanical losses | 8.1W | Angular speed | 170 | Power output | 206W |
| Stator eddy losses | 0.4W | Total power loss | 25.3W | Power coefficient | 0.36 |
| Copper losses | 0.001W | Power input | 231W | | |

The turbine's aerodynamic design considered the relationship between blade angle of attack, lift and drag forces, and the critical stall angle range (14.5°–15.5°).

**Generator Design**

An axial flux permanent magnet generator was developed for the turbine, utilizing a double-rotor, single-stator configuration. The design incorporated 12 magnets and 9 stator coils, arranged to maintain a 4:3 magnet-to-coil ratio, enabling efficient three-phase AC generation.

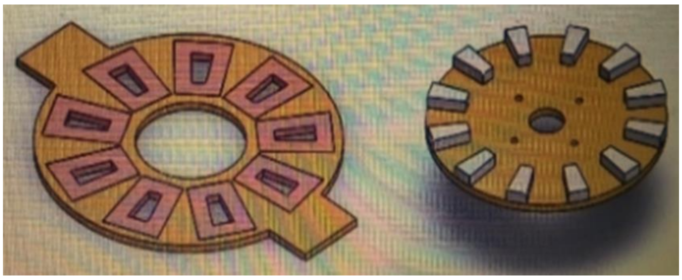

Figure 6. Model of Stator and Magnetic Disc

Two rotor discs were fabricated from composite materials, with embedded neodymium magnets positioned to maintain alternating polarity (N-S-N). The stator coils were wound using 16-gauge copper wire, with 108 turns per coil. An air gap of 4 mm was maintained between the stator and each rotor to optimize magnetic coupling and reduce cogging torque. The final generator specifications are presented.

Table 2. Parametric Specifications for Generator

| Parameter | Value | Parameter | Value | Parameter | Value |
|---|---|---|---|---|---|
| Outer radius of rotor | 0.185m | Air gap | 0.004m | Magnet width | 0.023m |
| Inner radius of rotor | 0.128m | Magnet poles | 12m | Gauge | $2 \times 10^{-6}$ m² |
| Stator axial length | 0.012m | Stator coils | 9m | Angular speed | 170rpm |
| Rotor/stator thickness | 0.015m | Magnet length | 0.056m | Turns per coil | 108 |

**Material Selection**

Lightweight composite materials were selected to maximize efficiency by reducing mechanical losses. The turbine blades were manufactured using fiberglass reinforced plastic (GFRP) with a thermocol (polystyrene) core, bonded with epoxy resin, as shown in Figure 7. This combination provided a high stiffness-to-weight ratio, corrosion resistance, and durability under outdoor operating conditions.

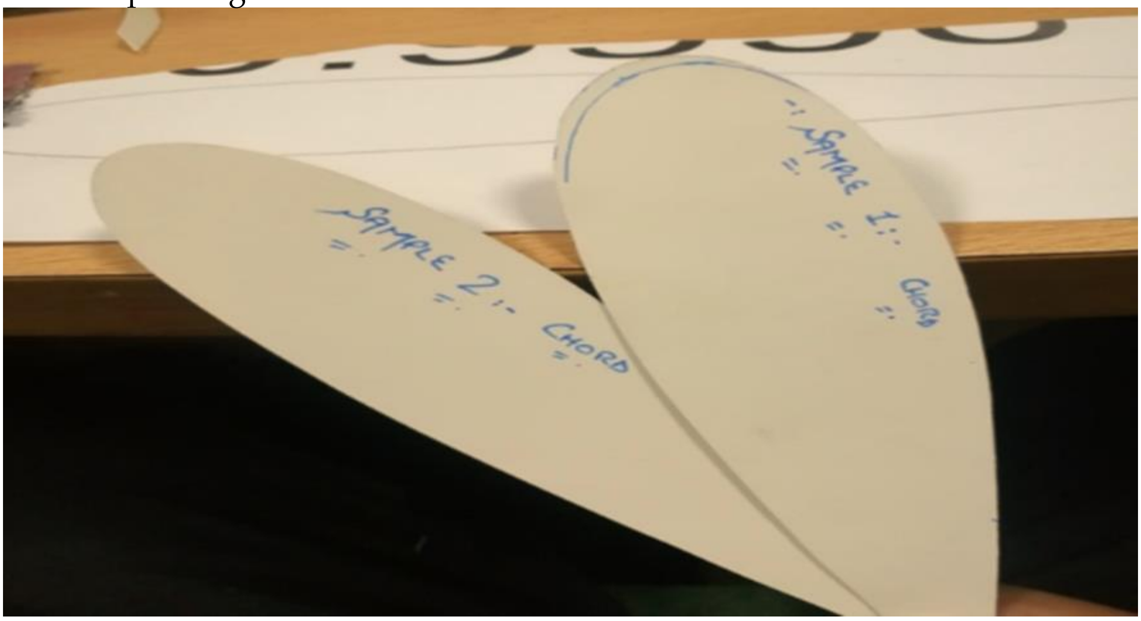


Figure 7. Samples of the Profile

**Manufacturing Process**

The blade profiles were cut from thermocol sheets using a hot-wire cutter, ensuring accurate replication of the NACA 0021 geometry. Aluminum clips were embedded in the core for mounting. Two layers of fiberglass were applied with epoxy resin to achieve the desired strength, followed by curing for 12–15 hours, as seen in Figures 8, and 9.

Figure 8. The Chord Attached to the Thermocol Sheet

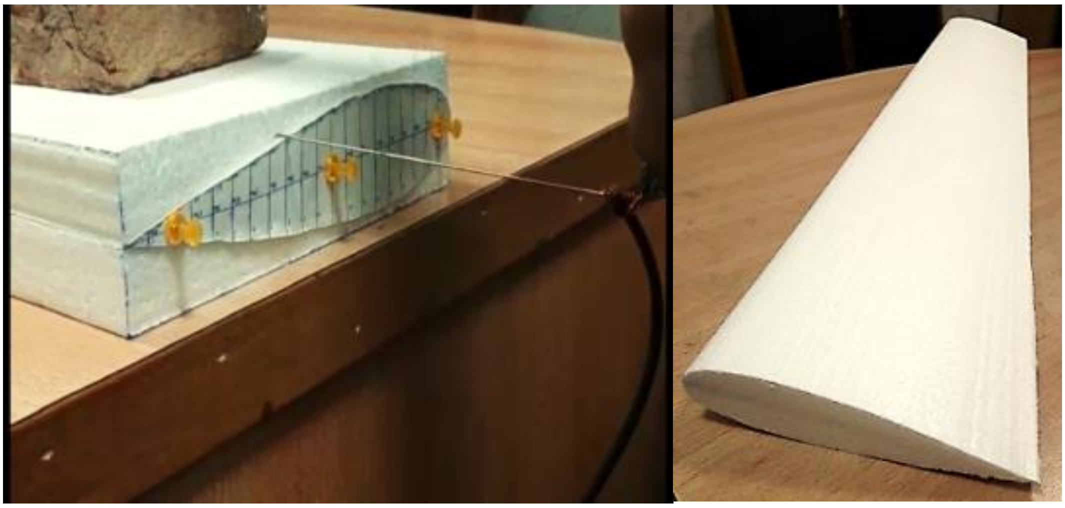

Figure 9. Hot Wire Cutting of Profile

The generator stator was fabricated by placing wound copper coils in a mold lined with fiberglass sheets, then filling with epoxy resin to create a rigid coil assembly. Rotor discs were prepared by embedding neodymium magnets into thermocol cores and coating them with fiberglass-epoxy layers for structural stability are shown in Figure 10.

Figure 10. Coil Adjustment & Epoxy Filling

Figure 11. Stator Coil Ring and Mold

**Assembly**

The final assembly involved mounting the stator on the turbine tower, attaching the rotor discs on either side of the stator, and securing the blades to the hub with aluminum struts. The fully assembled prototype was mounted for performance testing under controlled wind conditions.

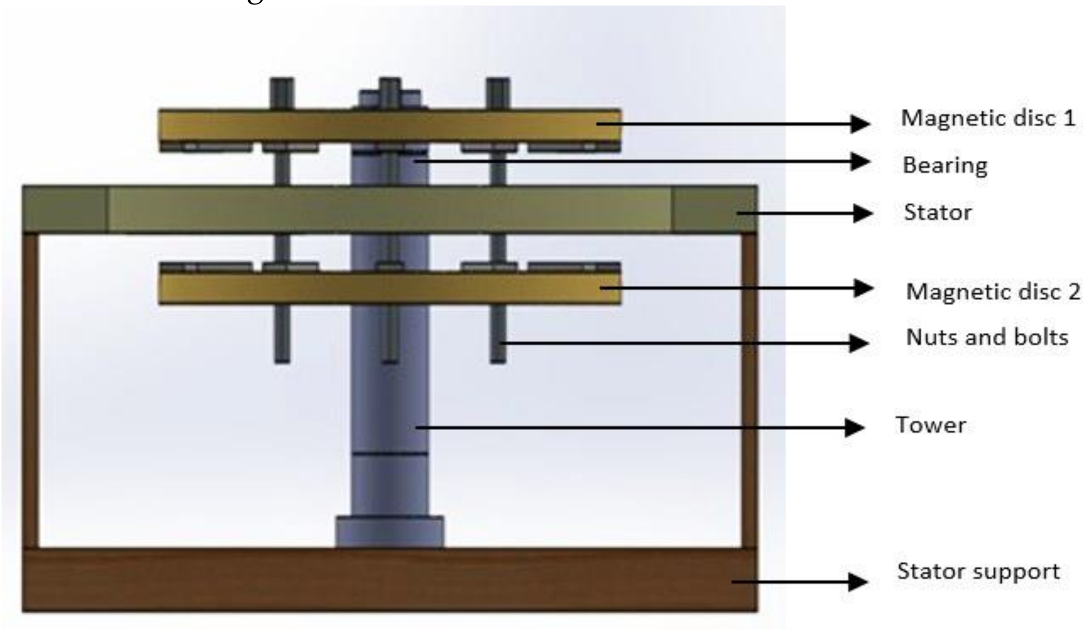


Figure 12. CAD Exploded View

Figure 13. Assembled Generator

## RESULT AND DISCUSSION

### Airfoil Profile Verification

The manufactured airfoil profile was compared with the standard NACA 0021 profile to ensure dimensional accuracy. Measurements showed close alignment between the designed and fabricated geometries, confirming that the hot-wire cutting and composite coating process preserved the aerodynamic shape.

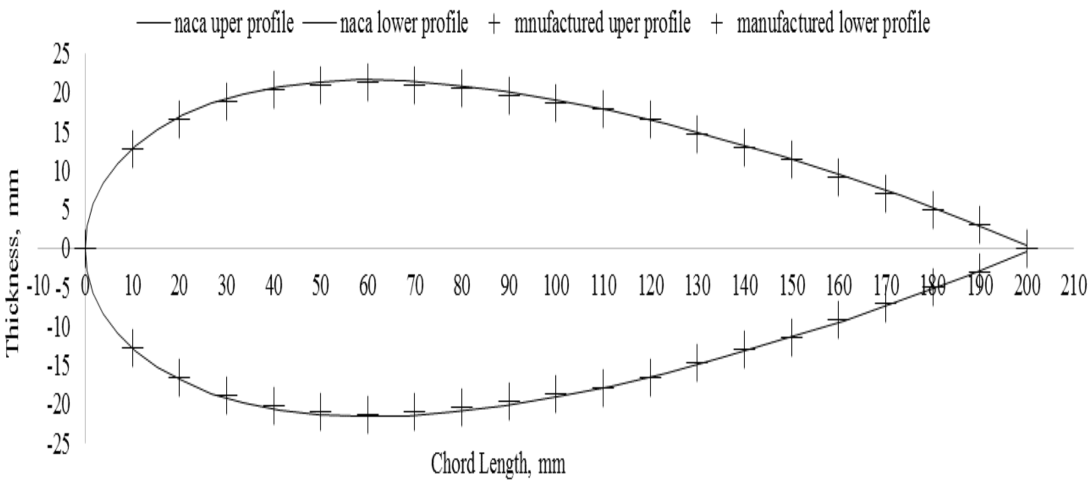


Figure 14. Manufactured Air Foil v/s NACA 0021

### Mechanical Testing of Composite Blade

The fiberglass–epoxy composite blade underwent a three-point bending test using a Universal Testing Machine (UTM, model WAW-500E). The aim was to evaluate strength, stiffness, and toughness. The specimen, with an area of 80,000 mm² and a weight of 845 g, demonstrated:

- Elastic limit at 20 mm deflection, stress of 0.17 MPa, and strain of 39%.
- Breaking point at 90 mm deflection, stress of 0.35 MPa, and strain of 180%.
- Upper yield strength: 16 MPa.
- Lower yield strength: 8 MPa.

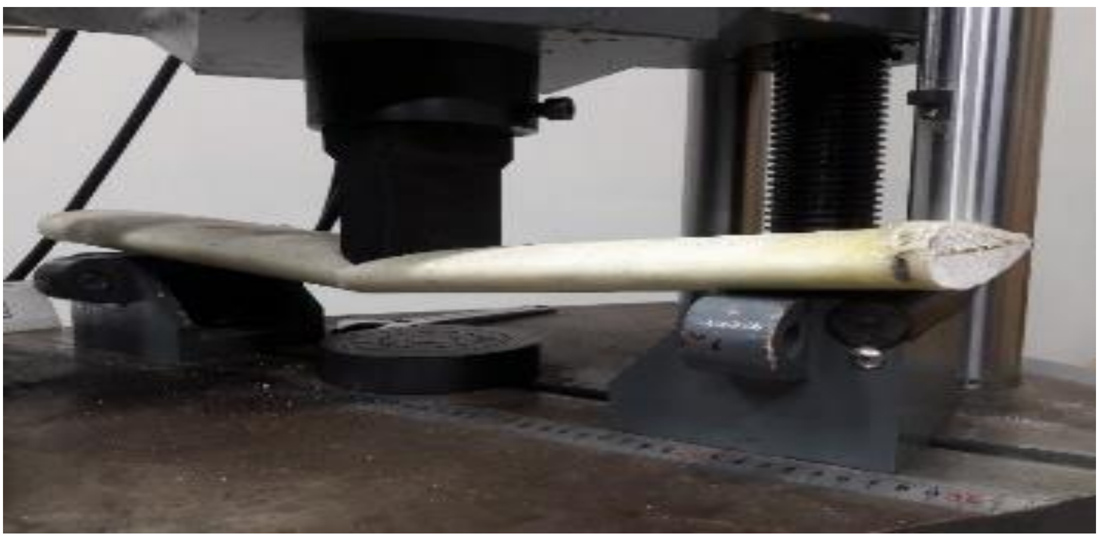

Figure 15. Testing of Turbine Composite Blade

The bending test revealed that blade deformation progressed slowly at low loads but increased rapidly beyond 60 s of loading, reaching peak load capacity (1.1 kN) at 78 s before permanent deformation began. Final fracture occurred at approximately 100 s under 0.6 kN load.

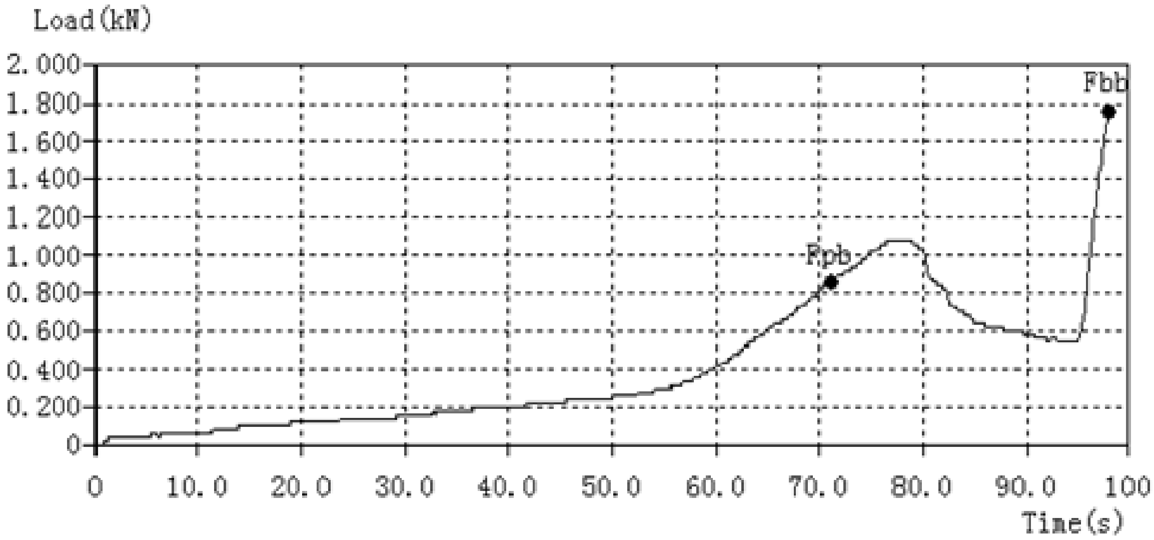


Figure 16. Load Time Curve

**Generator Performance Evaluation**

The axial flux generator was tested independently on a lathe machine to verify electrical output before blade attachment. Output voltage was measured at different rotational speeds with air gaps of 8 mm, 6 mm, and 4 mm. Results showed that reducing the air gap increased output voltage due to improved magnetic coupling. The generator produced a sinusoidal AC waveform, as observed on an oscilloscope (model SDS1052DL).

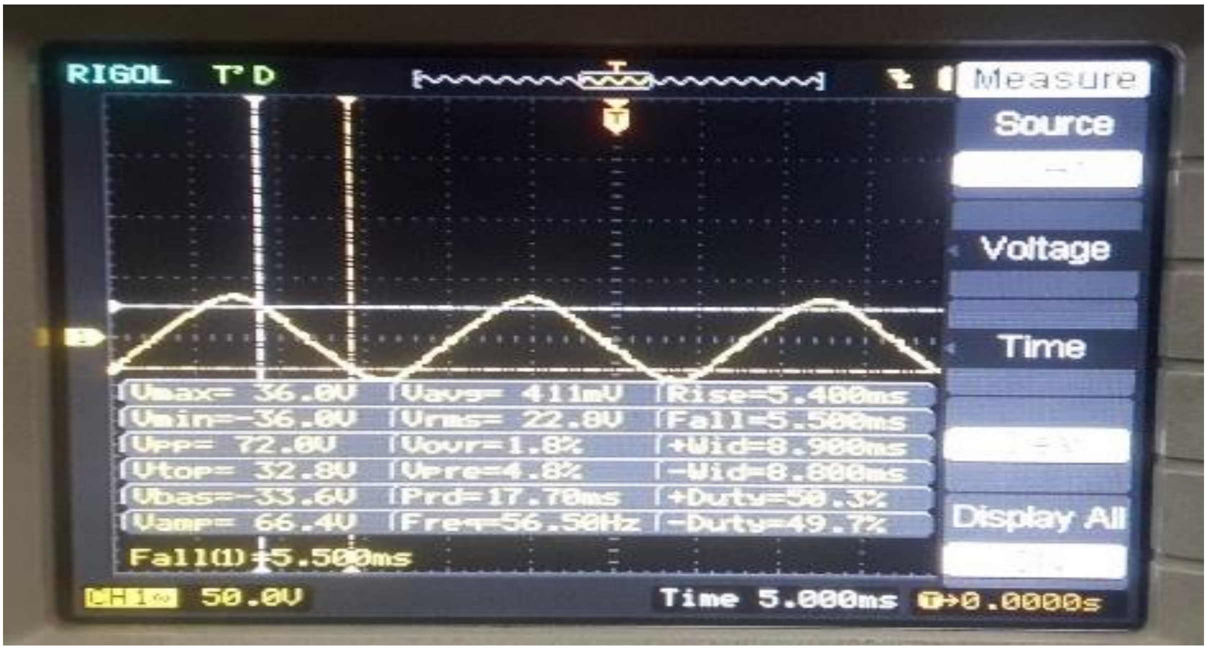


Figure 17. Power Measurement Unit of the Oscilloscope

**Turbine Power Output**

The complete VAWT prototype was tested using an artificial wind source (electric fan) at different wind speeds and angles of attack. A digital tachometer measured rotational speed, while voltage output was recorded using a digital multimeter.

1) Effect of Angle of Attack

Testing at wind speeds of 3 m/s, 4 m/s, and 5 m/s showed that optimal rotational speed occurred between 5° and 13° angle of attack, beyond which performance decreased due to stall effects.

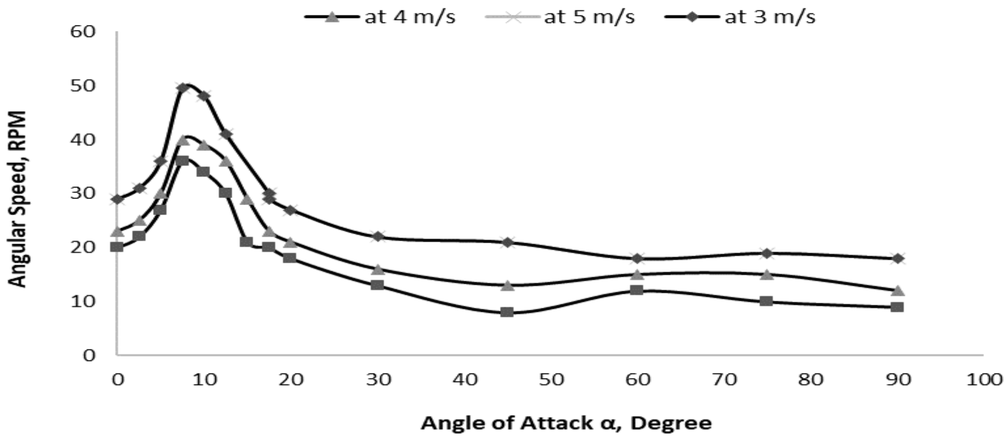


Figure 18. Effect of Angle of Attack on Turbine Speed

2) Effect of Angle of Attack

Voltage output increased proportionally with wind speed, as higher wind velocities increased the blade tip speed and generator rotational speed.

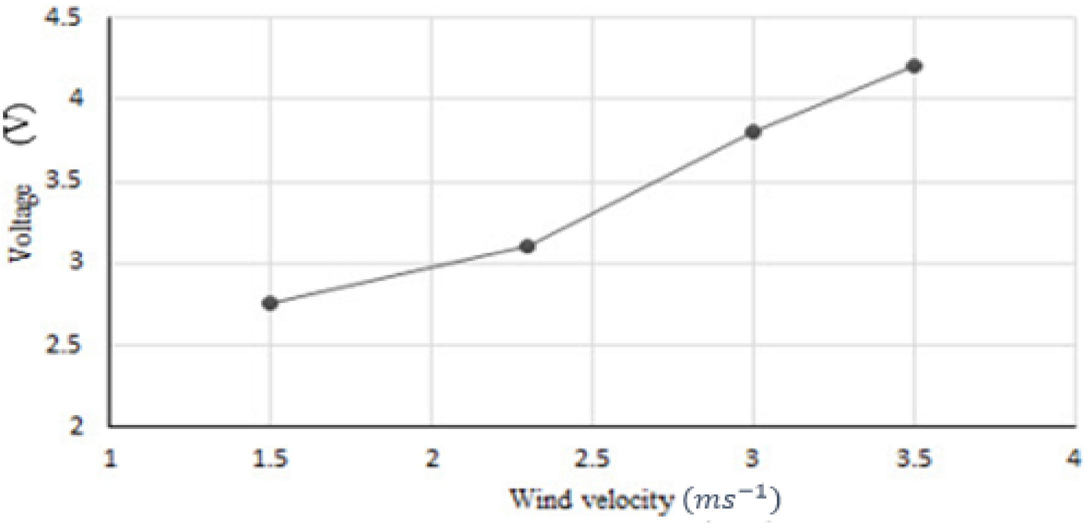


Figure 19. VAWT Power Output at Various Wind Speeds

Table 3. Summary of Key Performance Results

| **Parameter** | **Value** | **Parameter** | **Value** |
|---|---|---|---|
| Design wind speed | 8 m/s | Generator efficiency | 90% |
| Measured torque | 14.5 Nm | Net power coefficient | 0.36 |
| Mechanical power (rotor) | 257 W | Prototype cost | PKR 30,000 |
| Rotor efficiency (Cp) | 0.40 | Total weight | 20.3 kg |

**Proposed Work Discussion**

Results confirm that the NACA 0021 profile and composite construction provided the required strength-to-weight balance for efficient operation at low wind speeds. The generator's double-rotor, single-stator configuration achieved high efficiency, with minimal losses due to careful air gap optimization. The turbine achieved a power coefficient of 0.40 at the design speed, and 0.36 after accounting for generator losses, meeting the targeted design objectives. The total system cost and weight indicate strong feasibility for local manufacturing and deployment in both rural and urban environments.

## CONCLUSIONS AND RECOMMENDATIONS

This research successfully demonstrated the design, fabrication, and testing of a small-scale composite Vertical-Axis Wind Turbine (VAWT) optimized for low wind speed operation in Pakistan. The H-Darrieus configuration with NACA 0021 symmetric airfoil blades provided effective self-starting capability and high aerodynamic performance. Composite (GFRP) and thermocol resulted in a lightweight yet durable blade structure, reducing mechanical losses and improving overall efficiency.

The integrated axial flux generator, designed with a double-rotor, single-stator arrangement, achieved a high efficiency of 90% through optimized air gap settings. The prototype produced a torque of 14.5 Nm and mechanical power of 257 W at the design wind speed of 8 m/s, corresponding to a power coefficient (Cp) of 0.40, and an effective Cp of 0.36 after generator losses. The complete system cost was approximately PKR 30,000 with a total weight of 20.3 kg, demonstrating strong potential for low-cost, locally manufactured renewable energy solutions.

Future recommendations include implementing magnetic levitation bearings to reduce mechanical friction, improving rotor balance and fabrication precision for greater stability, and introducing a gearing mechanism to increase generator speed at low wind velocities. Additionally, refining composite manufacturing techniques will enhance consistency in blade strength, while the integration of a clutch and brake system will protect the turbine under extreme wind conditions. Together, these advancements can improve energy capture efficiency, reduce maintenance needs, and extend the operational lifespan of the system, making it a stronger candidate for distributed renewable power generation in Pakistan.

**Credit Authorship Contribution Statement**

Muhammad Sohaib Azeem: Writing–Original draft, Visualization, Software, Methodology, Investigation. Tasawar Abbas: Data curation, Writing–Review & Editing, Supervision, Visualization, Software, Methodology. X:

Formal Analysis, Data curation, Project Administration, Visualization. Y: Data curation, Formal Analysis, Visualization. Z: Data curation, Visualization, Project Administration.

**FURTHER STUDY**

All primary findings and contributions of this study are contained within the article. For additional information, please contact the corresponding author.

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