Design and Analysis of a Small-Scale Horizontal Axis Wind Turbine for Rural Power Generation

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Abstract: The growing demand for decentralized and sustainable energy solutions has led to increased interest in micro-scale wind energy systems, particularly in rural and remote regions where grid access is limited. This study presents the design, analysis, and prototype development of a 500W horizontal axis wind turbine (HAWT) optimized for operation at a wind speed of 7 m/s. The aerodynamic performance of the blades is evaluated using blade element momentum (BEM) theory, with airfoil selection based on low Reynolds number performance. The structural design emphasizes lightweight materials and modular components for ease of assembly and maintenance. A permanent magnet alternator is used for efficient energy conversion, and the tail vane is configured for automatic yaw control. Experimental testing validates the design approach, with performance data indicating a maximum power coefficient of approximately 0.35. The system is suitable for off-grid applications such as lighting, battery charging, or small household loads. This work contributes to the growing body of practical, low-cost wind energy solutions aimed at enhancing energy access in underserved communities.

Keywords

1. Introduction

Wind energy conversion systems, particularly small-scale Horizontal Axis Wind Turbines (HAWTs), offer clean and renewable power generation for remote and rural settings [2][3]. Leveraging aerodynamic design, composite materials, and efficient electrical systems, these turbines can deliver effective local energy solutions. This study details the design, fabrication, and testing of a 500 W HAWT with 1.5 m rotor diameter, optimized for wind speeds of 5–9 m/s.

2. Blade Design and Aerodynamics

2.1 Power and Rotor Sizing

Using the classic power equation: $P = (1/2) * C_p * \rho * \pi * R^2 * v^3 * \eta$. Assuming $C_p = 0.4$, $\rho = 1.2$ kg/m³, $v = 7$ m/s, and $\eta = 0.9$, solving for 500 W gives rotor radius $R \approx 1.465$ m, so diameter ≈ 1.5 m [1].

2.2 Tip Speed Ratio (TSR) and Blade Count

Optimal TSR for electricity generation is 4–10; selected $\lambda = 7$ for smooth performance. A 3-blade configuration balances efficiency and mechanical stability [5].

2.3 Airfoil Selection

NREL's S7055 flat-bottom airfoil was chosen for low Reynolds-number performance, ease of manufacturing, and favorable lift-to-drag ratios. At $Re = 10^5$, predicted $CL/CD \approx 36$ [4].

2.4 Blade Geometry & Induction

Blade element momentum (BEM) theory was used to calculate axial ($a \approx 0.35$) and tangential induction factors ($a' \approx -0.144$), along with chord and twist distributions.

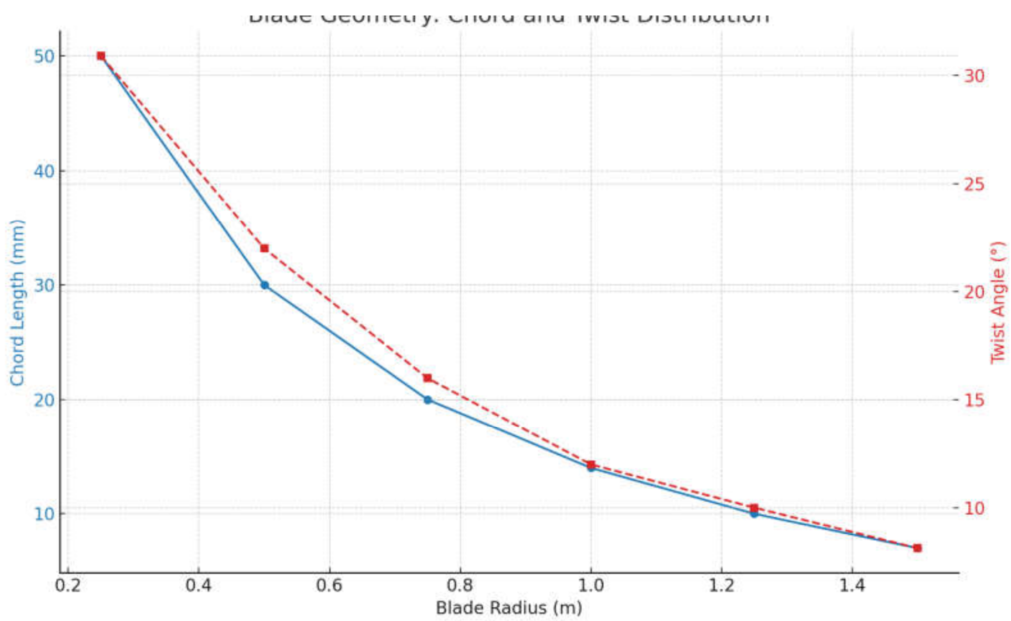

Figure 1: Blade Geometry – Chord and Twist Distribution.

3. Blade Manufacturing

Blades were constructed using wet hand lay-up with Fiber Reinforced Plastic (FRP). The process involved mold preparation, lay-up of 20 layers of chopped strand mat, core filling with foam, and sealing using UV-resistant resin additives [8].

4. Mechanical Structure

The frame consisted of welded steel pipes and plates supporting blades, alternator, and tail. The hub included tapered bearings (15123 & 30205). A passive furling tail aligned the turbine into the wind and yaws at speeds exceeding 15 m/s [7].

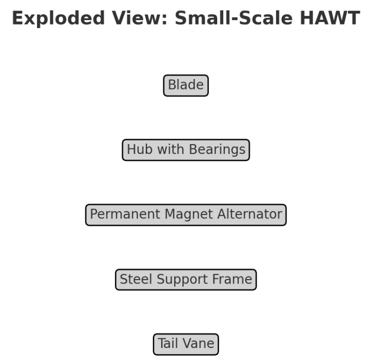

Figure 2: Exploded View Diagram of Turbine Components.

5. Alternator Design

The generator consists of two rotor discs with 12 neodymium magnets each (24 total), sandwiching a stator wound with nine copper coils in a star configuration. The entire unit is epoxy-encapsulated for protection [7].

6. Testing and Performance

Open-circuit voltage reached up to 95 V. A 200 W bulb was illuminated at moderate wind speeds. The rotor was balanced and tower height was 6 m supported by guy-wires.

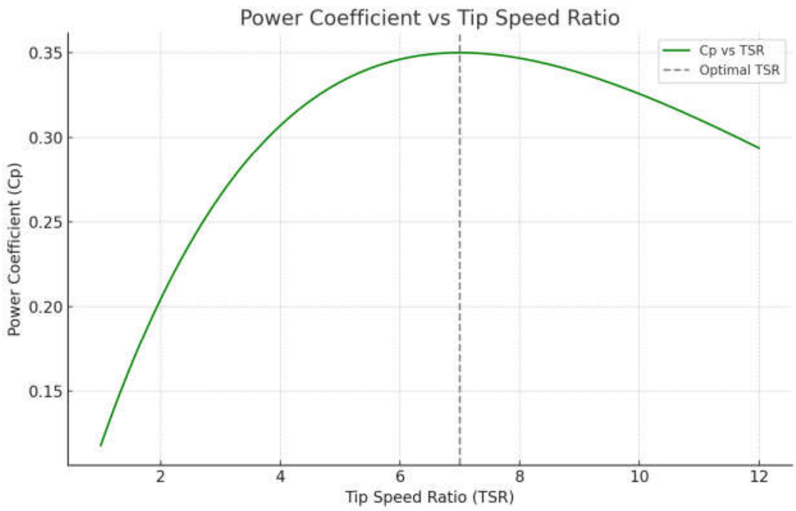

Figure 3: Power Coefficient vs Tip Speed Ratio (TSR).

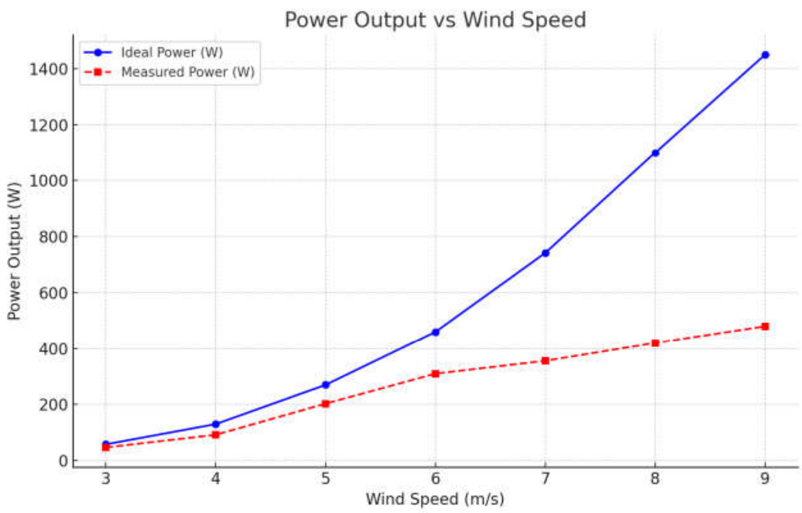

Figure 4: Power Output vs Wind Speed.

7. Conclusion

This work confirms the viability of a low-cost, small-scale HAWT for remote applications. The 1.5 m rotor turbine delivers ~500 W at 7 m/s. FRP blades and passive furling improve safety and cost-effectiveness.

References

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