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# Design and Construction of a Passive Control Three-Blade Prototype Horizontal Axis Wind Turbine

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## Abstract:

The design, construction, and performance evaluation of a three-blade prototype Horizontal Axis Wind Turbine (HAWT) incorporating a passive stall speed control system are presented. The research addresses recurring failures observed in wind turbine projects at Kaduna Polytechnic, Nigeria, which were attributed to the absence of effective overspeed protection during adverse wind conditions. The prototype was designed with a 1.5-metre tower fabricated from carbon steel and a 1-metre rotor diameter, with the rotor assembly constructed from locally sourced structural wood. The passive stall control mechanism exploits the blades' fixed geometric orientation relative to the angle of attack of the incoming wind, thereby requiring no dynamic mechanical components for speed regulation. Performance testing was conducted under both natural and artificially induced excessive wind conditions, using an anemometer, digital tachometer, and digital multimeter to measure wind speed, rotor RPM, and power output, respectively. The results confirm that the passive stall control effectively limits rotor speed under excessive wind conditions, preventing catastrophic structural failure while maintaining viable electrical output. This work demonstrates the feasibility of constructing reliable, locally fabricated small-scale wind turbines and establishes a framework for further research and development in community-based renewable energy solutions.

*Keywords* — Horizontal Axis Wind Turbine, Passive Stall Control, Speed Regulation, Prototype Design, Renewable Energy, Local Fabrication.

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## I. INTRODUCTION

The escalating global demand for clean and sustainable energy has positioned wind power as one of the most rapidly deployed renewable energy technologies. According to the Global Wind Energy Council, the installed global wind capacity exceeded 837 GW by 2021, reflecting a cumulative growth of 153% compared to 2020 [1]. Horizontal Axis Wind Turbines (HAWTs) constitute the predominant configuration in both utility-scale and small-scale installations, operating on aerodynamic lift principles to convert the kinetic energy of wind into rotational mechanical energy, which is subsequently converted to electrical energy through a generator [2].

A critical aspect of wind turbine operation is the limitation of rotor speed. Wind turbines are designed with maximum operational speeds beyond which catastrophic mechanical failure can occur. Excessive wind gusts, if unmitigated, can cause structural collapse of the rotor assembly, damage to the drivetrain, and potential hazards to surrounding infrastructure [3]. Consequently, all wind turbines must incorporate some form of speed control or overspeed protection mechanism. Several speed control strategies have been developed and deployed in the wind energy industry. The most widely recognized methods include active pitch control, furling, and passive stall regulation [4]. Each method presents distinct advantages and disadvantages in terms of complexity, cost, reliability, and energy capture efficiency.

Active pitch control involves the adjustment of blade pitch angles during operation to regulate the angle of attack and, consequently, the aerodynamic lift generated by the blades. In pitch-to-stall configurations, the blades are actively pitched into a stalled condition at high wind speeds to reduce power extraction [5]. While pitch control offers precise regulation and is the dominant method in modern utility-scale turbines, it requires complex electromechanical systems including servomotors, sensors, and control algorithms, making it prohibitively expensive for small-scale applications [6]. Furling is a mechanical overspeed protection method commonly employed in small wind turbines. In this approach, the nacelle assembly rotates about a furling hinge, angling the rotor out of the wind stream when wind forces exceed a predetermined threshold. While furling provides a simple and effective means of overspeed protection, it significantly reduces energy capture at high wind speeds and introduces additional noise and mechanical complexity through the furling mechanism itself [7]. Muljadi et al. [7] demonstrated that furling control results in poor energy capture at high wind speeds and proposed the soft-stall control method as a superior alternative for small wind turbines. Passive stall regulation, also known as stall regulation, relies on the inherent aerodynamic characteristics of the blade design to limit power output at high wind speeds. In this method, the blades are rigidly mounted to the hub at a fixed angle, with the blade geometry and twist distribution engineered such that the blades progressively stall as wind speed increases beyond the rated value [8]. The stall phenomenon causes a loss of lift and an increase in drag on the blade surface, naturally limiting the rotor speed without any active or moving mechanical components [4]. This approach is characterized by its simplicity, low cost, mechanical robustness, and rapid response to wind gusts [9].

The application of passive stall control in wind turbine design has been extensively documented in the literature. Muljadi et al. [10] developed a control strategy for variable-speed, stall-regulated wind turbines, demonstrating that controlling the rotor speed by specifying the demanded generator torque could effectively constrain power output without active aerodynamic control devices. Their experimental work on a 275 kW test bed confirmed that rotor speed and power output were well regulated through the soft-stall approach.

Macquart and Maheri [11] investigated the potential of variable-speed stall-regulated (VS-SR) wind turbines in reducing fatigue loads. Their study, based on the NREL 5 MW wind turbine as a baseline, showed that a well-designed VS-SR wind turbine experiences significantly less fatigue loads compared to pitch-controlled systems, with low power transients near and above rated wind speed. Their findings suggest that passive stall regulation can be as efficient as pitch control in power generation while offering superior structural longevity. Similarly, Martinez et al. [12] developed an improved Blade Element Momentum (BEM) model specifically for predicting the power curves of stall-regulated wind turbines, emphasizing the critical role of blade twist distribution and taper in ensuring gradual and controlled stall behavior. Their work established that the aerodynamic design of stall-regulated blades requires careful attention to the twist angle profile to avoid abrupt stall transitions that could cause damaging load spikes.

Mo and Lee [13] conducted computational fluid dynamics (CFD) investigations on the NREL Phase VI wind turbine operating with a stall-regulated method. Their analysis confirmed that stall regulation effectively constrains torque at high wind speeds, with the aerodynamic torque remaining approximately constant beyond a wind speed of 10 m/s, thereby protecting the turbine from overspeeding. Another work by Elkodama et al. [14] provided a comprehensive state-of-the-art review of control methods for HAWTs, noting that stall-controlled devices are deployed in approximately two-thirds of the world's installed wind turbines. Their review highlighted the continued relevance of stall regulation, particularly for small-scale and fixed-pitch configurations. Finally, Barzegar-Kalashani et al. [15] presented a comprehensive review of small-scale wind turbine control in high-speed wind conditions, concluding that while pitch control is widely used in medium- and large-scale turbines, such complex mechanisms are too expensive for small wind turbines. They recommended electrical stall control strategies integrated with Maximum Power Point Tracking (MPPT) algorithms as the most practical approach for small-scale applications.

Despite the documented advantages of passive stall control, there remains a significant gap in the practical knowledge and hands-on experience required to design and fabricate stall-regulated wind turbines within local communities, particularly in developing regions. At Kaduna Polytechnic, consistent failures observed in previous wind machine projects, especially during wind gusts, highlighted the absence of effective design measures to ensure the safety and reliability of these machines during adverse conditions. A noticeable deficiency in local knowledge and practical skills regarding the operation, design, and construction of wind turbines further exacerbated the situation. This research is driven by the recognition that these problems demand localised solutions, eliminating the reliance on imported technology and foreign expertise. The aim is to address these challenges within both the educational context and the broader community, fostering self-sufficiency and resilience in the development and maintenance of sustainable energy solutions.

## II. METHODOLOGY

### *A. Design Philosophy and Specifications*

The research adopted a systematic approach to the design and construction of a pedestal-mounted, three-blade HAWT. The design philosophy prioritized simplicity, reliability, and the use of locally available materials, in alignment with the goal of creating a community-appropriate renewable energy solution. The key design specifications are presented in Table 1.

**Table 1: Key Design Specifications**

| Parameter | Value |
|---|---|
| Turbine Type | Horizontal Axis Wind Turbine (HAWT) |
| Number of Blades | 3 |
| Rotor Diameter | 1.0 m |
| Tower Height | 1.5 m (minimum) |
| Tower Material | Carbon structural steel tube (1500 mm length, 3 mm wall thickness, 100 mm diameter) |
| Rotor/Blade Material | Structural wood (150 mm x 150 mm x 1500 mm cross-section) |
| Blade Mounting | Fixed angle of attack, rigid connection to hub |
| Speed Control Method | Passive stall (fixed geometrical dual orientation) |
| Generator | Small permanent magnet DC (PMDC) generator |
| Generator Coupling | Direct or through gearbox |

  

The selection of a three-blade configuration was motivated by the well-established balance between aerodynamic efficiency, structural stability, and starting torque characteristics of three-blade rotors [16]. The 1-metre rotor diameter was chosen to provide a manageable scale for prototype construction while still generating measurable electrical output.

### *B. Blade Design and Passive Stall Mechanism*

The blade design is the cornerstone of the passive stall control system. The blades were designed with a fixed geometrical dual orientation relative to the incoming wind flow. This dual orientation refers to the variation of the blade cross-sectional geometry along its span, such that different sections of the blade are oriented at different angles relative to the wind. As wind speed increases, the effective angle of attack at certain blade sections progressively exceeds the critical stall angle, causing flow separation and a consequent reduction in aerodynamic lift [12].

The blade profile was selected to ensure that the turbine operates at its optimal tip speed ratio at moderate wind speeds but transitions into a stalled condition as wind speeds exceed the rated threshold. The angle of attack at the blade root was set at a higher value compared to the tip, creating a progressive stall pattern from root to tip that ensures smooth power limitation rather than abrupt stall events [8].

### *C.* Simulation and Modelling

The design phase commenced with the three-dimensional modeling of the HAWT blade using SolidWorks computer-aided design (CAD) software. The blade geometry was defined parametrically, with variables for chord length, twist angle, and airfoil profile along the blade span. Computational analysis was performed to evaluate the aerodynamic performance of the blade at various wind speeds and to predict the onset of stall conditions.

The simulation results informed the final blade dimensions and the twist distribution profile. A three-blade rotor assembly was then modeled in SolidWorks to verify the structural integrity of the hub-blade connections and to assess the dynamic balance of the rotor under simulated wind loading conditions.

### *D. Construction and Assembly*

Following the completion of the simulation phase, the physical construction was carried out in a structured sequence. The procurement of materials and equipment was the first step, including the acquisition of carbon steel structural tubing for the tower, structural wood for the rotor assembly, and the necessary measuring instruments.

Tower Construction: The tower was fabricated from a carbon steel tube with dimensions of 1500 mm in length, 3 mm wall thickness, and 100 mm outer diameter. A pedestal base was welded to the bottom of the tower to provide a stable mounting platform. The tower was erected vertically and secured to a concrete foundation to withstand the overturning moments generated by wind loads.

Rotor Assembly: The three blades were machined from structural wood blocks measuring 150 mm by 150 mm in cross-section and 1500 mm in length. The blade profiles were shaped using woodworking tools to achieve the required airfoil geometry and twist distribution as determined by the simulation phase. The blades were then mounted rigidly to a central hub at the predetermined angle of attack, ensuring equal spacing of 120 degrees between each blade.

Generator Coupling: The rotor assembly was coupled to a small permanent magnet DC (PMDC) generator, either directly or through a speed-increasing gearbox, depending on the optimal speed ratio for the selected generator. Bearings were installed at the nacelle to support the rotor shaft and minimize frictional losses.

### *E.* Performance Testing and Instrumentation

The assembled prototype was subjected to comprehensive performance testing under two categories of wind conditions: natural wind conditions and artificially induced excessive wind conditions. The artificial wind was generated using industrial fans to simulate wind gusts exceeding the turbine's rated operating speed. The following measuring instruments were employed during testing:

**Table 2: Measuring Instruments**

| Instrument | Parameter Measured | Purpose |
|---|---|---|
| Digital Anemometer | Wind speed (m/s) | Characterize the wind resource during testing |
| Digital Tachometer | Turbine rotational speed (RPM) | Monitor rotor speed and verify stall limiting |
| Digital Multimeter | Voltage and current output | Calculate electrical power output |
| AC/DC Clamp Meter | Current draw | Cross-verify power measurements |
| Digital Magnetic Flux Meter | Magnetic field intensity | Assess generator field strength |

## *III. Results and Discussions*

### *A. Aerodynamic Performance Under Normal Wind Conditions*

During testing under natural wind conditions at moderate speeds (below the rated wind speed), the turbine demonstrated satisfactory aerodynamic performance. The rotor accelerated smoothly from the cut-in speed, and the power output increased proportionally with the cube of the wind speed, as predicted by the fundamental wind power equation:

$$P = 0.5 \text{ x } rho \text{ x } A \text{ x } Cp \text{ x } V\hat{}3$$

where P is the power extracted from the wind, rho is the air density, A is the rotor swept area, Cp is the power coefficient, and V is the wind speed.

The turbine achieved its maximum power coefficient at the designed optimal tip speed ratio, confirming that the blade geometry and twist distribution were correctly implemented. The measured performance data at moderate wind speeds are summarised in Table 2.

**Table 3: Measured Performance**

| Wind Speed (m/s) | Rotor Speed (RPM) | Power Output (W) |
|---|---|---|
| 3.0 | 120 | 2.1 |
| 4.0 | 165 | 5.8 |
| 5.0 | 210 | 12.4 |
| 6.0 | 248 | 22.7 |
| 7.0 | 275 | 35.6 |
| 8.0 | 295 | 48.2 |
| 9.0 | 308 | 55.3 |
| 10.0 | 315 | 58.1 |

The data reveals a clear trend of increasing power output with wind speed up to approximately 10 m/s, at which point the rotor speed begins to plateau and the power output ceases to increase proportionally. This transition marks the onset of the passive stall control mechanism

### *B. Passive Control Under Excessive Wind Conditions*

The critical test of the passive stall control system was conducted under artificially induced excessive wind conditions, where wind speeds were elevated beyond the turbine's rated operating range using industrial fans. The results, presented in Table 3, demonstrate the effectiveness of the speed control mechanism.

**Table 4: Effectiveness of Speed Control Mechanism**

| Wind Speed (m/s) | Rotor Speed (RPM) | Power Output (W) | Stall Status |
|---|---|---|---|
| 10.0 | 315 | 58.1 | Beginning of stall |
| 11.0 | 318 | 57.4 | Partial stall |
| 12.0 | 320 | 55.8 | Stall engaged |
| 13.0 | 319 | 53.2 | Full stall |
| 14.0 | 316 | 50.7 | Sustained stall |
| 15.0 | 312 | 47.5 | Sustained stall |

The results clearly show that as wind speed increased from 10 m/s to 15 m/s, the rotor speed remained essentially constant, fluctuating between 312 and 320 RPM. This constitutes a speed variation of less than 2.5%, demonstrating that the passive stall control successfully limited the rotor speed despite a 50% increase in wind speed. The power output, while decreasing slightly due to the increasing severity of the stall condition, remained within a stable and safe range.

### *C. Effectiveness of the Stall Control System*

The effectiveness of the passive stall control system can be quantified by comparing the rotor speed behavior with and without the stall mechanism. In an unconstrained turbine (without any speed control), the rotor speed would increase linearly with wind speed, potentially reaching dangerous levels that could cause structural failure. The measured data confirms that the fixed geometrical dual orientation of the blades effectively induced aerodynamic stall at the critical wind speed, limiting the rotor speed to a safe maximum of approximately 320 RPM. The stall control mechanism exhibited several notable characteristics during testing. First, the response to increasing wind speed was rapid, with the stall condition engaging within seconds of the wind speed exceeding the threshold. Second, the stall was progressive rather than abrupt, resulting in smooth power regulation without the violent load fluctuations associated with sudden stall events. Third, the system demonstrated self-recovery behavior: as wind speed decreased below the stall threshold, the blades naturally regained their aerodynamic efficiency and the turbine returned to normal operation without any manual intervention.

### *D. Impact on Power Output Performance*

The passive stall control mechanism inevitably affects the power output of the turbine at high wind speeds. The data shows that the maximum power output of approximately 58.1 W was achieved at a wind speed of 10 m/s, beyond which the power output decreased to 47.5 W at 15 m/s. This represents a power reduction of approximately 18.2% compared to the peak value. However, this power reduction must be contextualized within the primary objective of the control system, which is the prevention of catastrophic failure. The alternative of uncontrolled overspeeding would result in rotor speeds exceeding the structural limits of the turbine, potentially causing blade fracture, bearing failure, or tower collapse. The 18.2% power reduction at extreme wind speeds is a minor trade-off for the substantial increase in operational safety and turbine lifespan. Furthermore, it should be noted that wind speeds exceeding 15 m/s are relatively rare in most geographical locations, and the turbine would spend the majority of its operational life in the optimal power generation range below the stall threshold. The overall energy yield, integrated over a typical year of operation, is therefore minimally affected by the passive stall control mechanism.

### *E. Structural Integrity and Material Performance*

The structural integrity of the prototype was verified throughout the testing programme. The carbon steel tower withstood all wind loads without visible deformation or structural distress. The structural wood blades performed admirably under both normal and excessive wind conditions, showing no signs of cracking, delamination, or permanent deformation. The rigid blade-hub connections maintained their integrity throughout all test runs, confirming the adequacy of the fastening system. The use of locally available materials proved to be both technically adequate and economically advantageous. The total cost of materials for the prototype was significantly lower than comparable imported turbine systems, validating the approach of utilizing local resources for renewable energy project development.

## IV. CONCLUSIONS

This research successfully designed, constructed, and evaluated a three-blade prototype Horizontal Axis Wind Turbine with a passive stall speed control system. The following conclusions are drawn from the study:

The passive stall control mechanism, based on the fixed geometrical dual orientation of the blades, proved highly effective in limiting rotor speed under excessive wind conditions. The rotor speed was maintained within a narrow band of approximately 312 to 320 RPM across wind speeds ranging from 10 m/s to 15 m/s, representing a speed regulation accuracy of better than 2.5%.

The progressive stall behavior of the blade design ensured smooth power regulation without violent load fluctuations, thereby minimizing the mechanical stress on the turbine structure and extending the operational lifespan of the machine.

The use of locally available materials, specifically structural wood for the rotor assembly and carbon steel for the tower, demonstrated that reliable and economically viable wind turbines can be fabricated within the community without dependence on imported components or foreign expertise.

The prototype successfully addressed the recurring failures observed in previous wind machine projects at Kaduna Polytechnic, establishing a viable model for other regions with similar conditions and resource availability.

The total reduction in power output at extreme wind speeds was approximately 18.2% compared to the peak value, which is an acceptable trade-off for the substantial improvement in operational safety and structural reliability.

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