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ORIGINAL RESEARCH ARTICLE

PERFORMANCE ANALYSIS OF HORIZONTAL AXIS WIND TURBINE USING VARIABLE BLADE PITCH CONTROL MECHANISM

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ABSTRACT

This work investigates the performance of a horizontal axis wind turbine (HAWT) with variable blade pitch control mechanism. The control mechanism is a simple mechanical Watt governor design, which was developed to regulate the blade pitch angle of the HAWT depending on wind speed magnitude. The HAWT model with the control mechanism was tested for performance in a wind tunnel. Response of the control mechanism in terms of blade pitch angle, rotor speed and generator power output were analyzed based on regulated predetermined wind speeds. The result shows a gradual increase in rotor speed and a proportional increase in generator power output between cut-in wind speed of 2.5m/s and rated wind speed of 6 m/s. These parameters were kept constant at 100 RPM and 50 Watts as observed due to the steady response of the control mechanism. The steadiness lasted up to a cut-out wind speed of 9 m/s. The control mechanism subsequently shutdown the turbine at the cut-out wind speed to protect the turbine against wind speeds higher than 9 m/s. The performance test predicts that the variable blade pitch control mechanism was able to regulate and bring about the require control of HAWT model. The mechanism allows the turbine to only operate between 2.5 and 9 m/s at blade pitch angle between 82 and 90 degrees from the axis of wind flow and change in governor height between 0 to 8 mm.

1.0 Introduction

Wind is a form free-flowing green energy caused by the uneven heating of the atmosphere by the sun. Wind possesses kinetic energy which can be captured and converted into other useful means especially electrical energy through the use of wind turbines (Ngo and Natowitz, 2009). Horizontal Axis Wind Turbine (HAWT) is the most common type of wind turbines used for extracting kinetic energy from wind because of its low cut-in wind speed, easy furling and relatively high power coefficient. It is a type of wind turbine that has wind flowing along the axis of rotation of its rotor (Daminia and Petal, 2013). In capturing part of the kinetic energy (KE) in the wind and convert same to other forms of useful energy (electricity), the HAWT is subjected to stochastic high wind speed phenomena. This is disastrous to the wind turbine causing generator burnout, rotor and tower failure (Shuwa et al. 2016).

While power is being captured from the wind by the HAWT, it is desired that the wind turbine be design to a wind speed that will not exceeds it critical limit and develop a control system that

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will make it operate within a safe wind speed range. This is in order to avoid unforeseeable damages to the machine structure and highly fluctuating power output under high wind speeds (Soriano et al, 2013). The aerodynamic forces on the rotor can be controlled to limit the speed of the HAWT by employing blade pitch control mechanisms as shown in Figure 1. It involves the use of centrifugal force to regulate and control the blade pitch angle depending on wind speed magnitude (Chen et al, 2014).

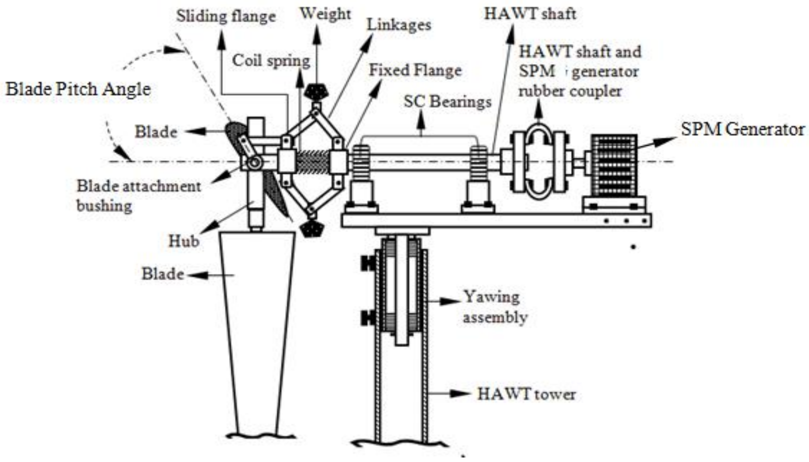

Figure 1: The HAWT with a simple mechanical blade pitch control Mechanism

The blade pitch control mechanism could be the Active Pitch Control (APC) or Passive or Stall Pitch Control (PPC or SPC). In the active pitch control the rotor blades turn around their longitudinal axis to the pitch by a speed controlled system that is usually computer type. Even though this type of control provide good pitch control, but its equipment are too expensive to afford. Hence the need for an alternative type of control system especially in small HAWT as used in low wind speed region. While the Passive or Stall Pitch Control (PPC or SPC) the blade does not rotate around its longitudinal axis, rather the blade is designed to naturally create a stall and lower rotational speed of the rotor. This requires structurally strong towers and that the blade is precise in its design and this is an additional expense on the total cost of the turbine (Maheswari and Tamilvendhan, 2012).

The principle of a simple mechanical Watt governor is applied in order to regulate the blade pitch angle of the HAWT which depends on the magnitude of the wind speed the turbine is subjected to. A Watt governor (typically centrifugal governor) is a device that will be used to measure and regulates the speed of a machine (Rana et al, 2012). Date back to 17th century; watt governors have been used to regulate the distance and pressure between millstones in windmills. Although, the early steam engines employed a purely reciprocating motion and were used for pumping water, an application that could tolerate variations in the working speed of machines (Navathale et al, 2017). Presently, the watt governor type is used to control the rotor speed of a three blades HAWT model, the blades was designed and developed by Shuwa et al (2016). The aim of this work is carry out a performance analysis of a horizontal axis wind turbine using variable blade pitch control mechanism. Response of the control mechanism measured in terms of blade pitch angle, rotor speed and generator power output with respect to change in wind speed, these parameters are analysis to determine if the desired HAWT control is achieved.

2.0 Methodology

A horizontal axis wind turbine blade geometry developed by Shuwa et al (2016) was scaled down to 1:10 based on the principle of dimensional analysis and similitude and used in this

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work. A watt governor was used to regulate the blade pitch angle of the HAWT model depending on wind speed magnitude. The model was tested for performance in a wind tunnel at the Department of Mechanical Engineering, University of Maiduguri. Response of the control mechanism was determined at regulated predetermined wind speeds in terms of rotor speed, blade pitch angle and generator power output. Cut-in, rated and cut-out wind speeds of the HAWT model were also established.

2.1 The HAWT Blade

The blade geometry developed by Shuwa et al (2016) for a micro HAWT was modified and used for the HAWT model analysis in this work. The modified blade parameters and its specification are shown in Table 1.

Table 1 Modified HAWT Blade Parameters and its Specifications

Parameter	Specification	Scaled Down Specification
Chord Length (C), m	0.26	0.024
Blade Span (L), m	1.5	0.15
Rotor Diameter (D), m	3	0.3
Number of Blades (n)	3	3
Swept Area (A), m^2	7.55	0.755
Tip Speed Ratio (λ_r)	5	5
Angle of Attack (θ), degrees	8	8
Wind Relative Angle (ϕ), degrees	48	48
Reynolds Number	3×10^6	3×10^6
Solidity Ratio (σ)	0.08	0.08

2.2 Operational Principle of the HAWT Blade Pitch Control Mechanism

The HAWT blade pitch control mechanism is a simple mechanical control system that works on the principle of centrifugal governor also known as Watt governor. A centrifugal governor is based on the balancing of centrifugal force on the rotating balls by an equal and opposite radial force. It consists of three balls of equal weights, which are attached to the arms called linkages as shown in Figure 2.

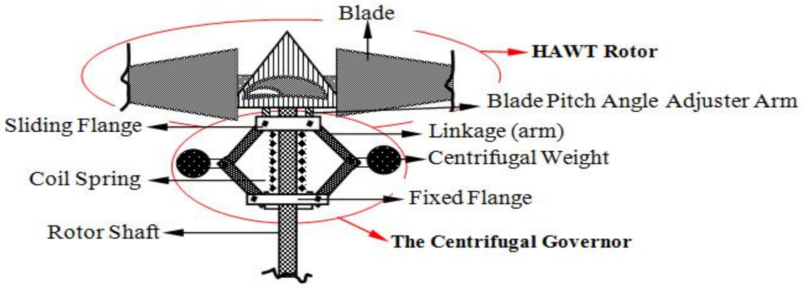

Figure 2: Centrifugal Governor on the HAWT rotor shaft

The balls revolve with the rotor depending on wind speed magnitude. The upper ends of the arms are pivoted to the blade shaft in the hub, so that the balls may pull outward or inward as they revolve about the rotor axis. The arms connect the sliding and fixed flange or sleeve. The fixed flange is keyed to the rotor shaft and the sliding flange moves to and fro against a spring according to the speed of the rotor. The movement of the sliding flange determines the change in governor height (Δh) of the control system. The balls pull out due centrifugal force when the

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rotor speed increases due increase in wind speed. When this occurs the balls move the sliding flange against the spring (governor height) to reduce the blade pitch angle (wind to blade angle of attack) which reduces the speed of the rotor. The balls (weights) push inwards due to the spring action when wind speed decreases. This increases the blade pitch angle and reduces the angle of attach to maintain safe rotor speed. The travel of the sliding flange is limited by the maximum compression limit of the coil spring and as wind speed exceed critical limits the sliding flange luck up to short down the turbine.

2.3 Design of the Blade Pitch Angle Control Mechanism

The HAWT control system is a mechanical control process designed based on a nonlinear closed-loop (feedback) control action govern by a second order nonlinear differential equation given by Equation 1.

$$\mathrm{F_{ac}} = \mathrm{M}\frac{\mathrm{d^2h}}{\mathrm{dv^2}} + \mathrm{B_c}\frac{\mathrm{dh}}{\mathrm{dv}} + \mathrm{K_s h} \qquad (1)$$

The applied centrifugal force ($\mathrm{F_{ac}}$) is generated by the fly masses (M) due to the rotational speed of the rotor (ω_r) as a result of increase in wind speed (v). The applied centrifugal force generate a displacement (h) against an opposing force due spring elasticity with a spring constant ($\mathrm{K_s}$). The speed of the rotor which is the input signal to the control system determines the change in the displacement of the sliding flange which regulates the blade pitch angle. Change in displacement of the sliding flange or sleeve (($\Delta\mathrm{h}$)) from its rest or initial (minimum) position to its maximum position due the applied centrifugal force was obtained using Equation 2. The minimum and maximum displacement of the sliding flange also indicates limits of the control system.

$$\Delta\mathrm{h} = \mathrm{BB^1} \cdot \cos\Delta\theta \qquad (2)$$

Where: BB1 is the maximum travel of the slider flange in mm and is equal to the radius of the blade pitch circle BK, while α the blade pitch angle and θ is the blade angle of attack as in Figure 2 given by Equation 3 and Δh is the sleeve travel from point B to B1.

$$\theta = \tan^{-1}\left(\frac{20\mathrm{v}}{\pi\mathrm{Nr}}\right) \qquad (3)$$

v is the wind speed, N is the speed of the rotor and r is the radius of the rotor.

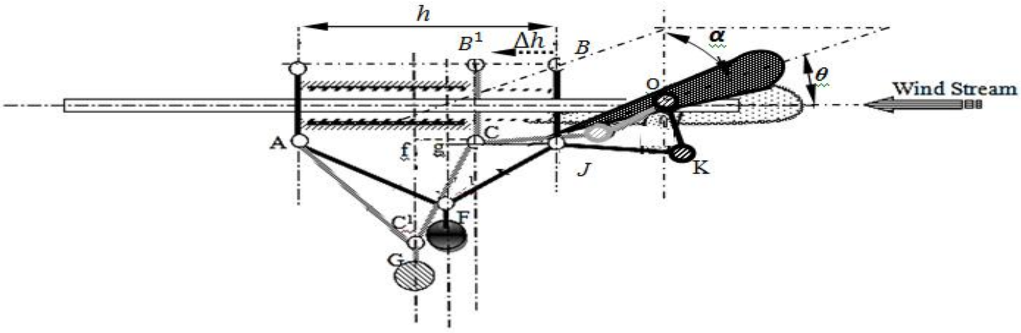

Figure 3: Section of the blade pitch angle control mechanism

As the sliding flange travel increases from point B to B1 due to increase in wind speed so will the blade pitch angle, thus reducing the blade angle of attack. The change in blade pitch angle α due change in wind speed is determined from Equation 4.

$$\Delta\alpha = \Delta(90 - \theta) \qquad (4)$$

The slider flange travel due to generated centrifugal force is against a spring. The spring used on the control system was a coiled compression spring. The function of the spring was to restores back the blade to its original angle of attack gradually as the wind speed decreases. The spring constant ($\mathrm{K_s}$) determines the ability of the spring to store and release back the stored

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energy as the magnitude of the applied centrifugal force decreases. The spring constant (K_s) is determined from Equation 5.

$$K_s = \frac{Gd^4}{8N_sD^3} \qquad (5)$$

Where: G is the spring's material modulus of elasticity, D_s is the spring coil diameter, d_s is the wire diameter, N_s is the number of spring active turns and C is the spring index given by ${}^{D_s}/_{d_s}$.

Moreover, determined experimentally in a wind tunnel test is the response of the control system in terms of rotor speed, blade pitch angle and generator power output based regulated predetermined wind speed. Determined also are cut-in, rated and cut-out wind speed of HAWT model with transient and steady response of the control mechanism under the changing wind speed.

2.4 Experiment Performed on the Developed HAWT in a Wind Tunnel

The Horizontal Axis Wind Turbine (HAWT) model developed with the scale down blade and the blade pitch control mechanism was tested in a wind tunnel (Figure 4). The wind turbine was subjected to variable wind speeds profile generated in the tunnel (from 1 to 10 m/s). Performance of the turbine in terms of rotor speed, blade pitch angle and generator power output speed were examined under a wind tunnel predetermined different wind speed conditions. Detail of the wind tunnel in terms of size and capacity alongside the types of instrument used are in Table 2.

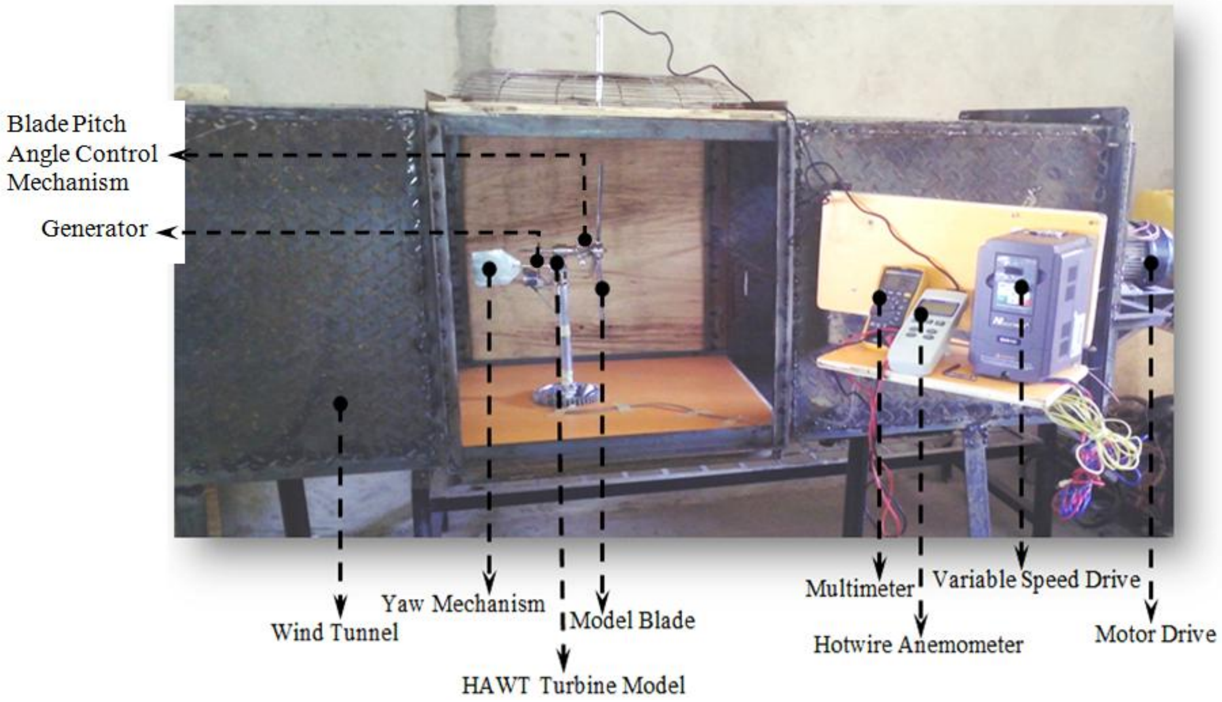

Figure 4: The HAWT model in an experimental wind tunnel assembly

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Table 2: Descriptive parts of the wind tunnel and its associated instrument

S/No.	Name of Instrument	Make	Model
1	Wind Tunnel Type	UM-ME	Open Ends Type
2	Wind Tunnel Size	-	600 × 600 × 3000 mm
3	Wind Tunnel Motor Drive	Atlas MT	Atlas 0054 4.4 kW 2900 rpm WT Fan Drive
4	Wind Tunnel Drive Control	Easy Drive	CVR 106 Regulates WT Air Flow/Velocity
5	Multimeter	Fluke RMS	117 TRUE RMS Voltage
6	Hot Wire Anemometer	Ctlutron YK	YK-2004 AH Air Velocity, Temperature
7	Optical Tachometer	COMPACT C.	CP No 003201 Revolution over Time

3.0 Results and Discussion

Performance analysis of the HAWT model with the blade pitch control mechanism developed based on the design parameters in Table 3.

Table 3: Design Parameters of the HAWT model and blade pitch control mechanism

Parameter	Value
Tower Height (TH), mm	200
Rotor Radius (r), mm	300
Blade Angle of Attack (θ), °	8
Blade Chord Length (C), mm	25
Drag Force (FD), N	0.023
Coefficient of Drag (CD),	0.0125
Lift Force (FL), N	0.19
Coefficient of Lift (CL)	1.007
Reynolds Number	$3x10^6$
Solidity Ratio (ς)	0.08
Power Coefficient (CP)	0.189
Turbine Theoretical Efficiency (η) %	32
Ultimate Wind Speed ($v_{ulti.}$)	9
Extractable Power from the Wind (P), Watts	27.22
Change in Governor Height (Δh), mm	0 to 8
Mass of the Centrifugal Weight (m), kg	0.09
Deflection of the Governor Spring (δ), mm	4.32
Spring Rate (K), N/mm	0.232

Figure 5 shows the response of the blade pitch control mechanism in terms of blade pitch angle and rotor speed with respect to wind speed range between 0 to 10 m/s at intervals of 0.5 m/s.

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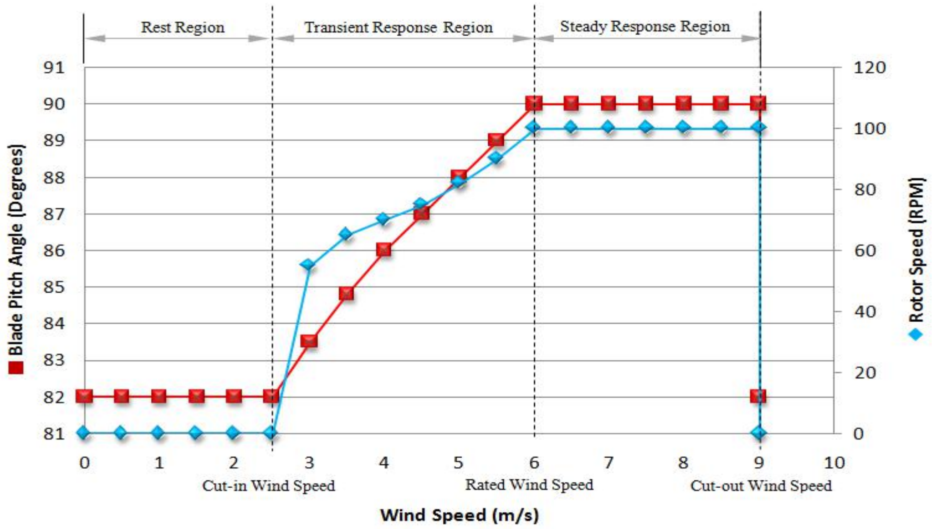

Figure 5: Response of the control mechanism in terms of blade pitch angle and rotor speed

The blade pitch angle and rotor speed indicate that, below cut-in wind speed of 2.5 m/s the system is in rest position. This result shows that from 0 to 2.5 m/s the blade pitch angle (82°) and rotor speed (0 RPM) remain constant, thus indicating that the turbine is at rest. The transient response of the control mechanism in terms of wind speed is between 2.5 m/s (cut-in wind speed) and 6 m/s (rated wind speed). The control mechanism stabilizes the blade pitch angle and rotor speed above wind speeds of 6 m/s and shutdown the turbine as wind speed reaches 9 m/s. Chan and Shiah (2016) revealed that an effective control mechanism shall be able regulate the blade pitch angle based on their rotational speed at the rotor and wind speed magnitude. Similarly, the current test results showed that the control mechanism increases the blade pitch angle as rotor speed increases with increase in wind speed. Moreover, change in governor height (Δh) from 0 to 8 mm of the blades pitch control mechanism due to increase in rotor speed, the mechanism gradually rotates the blade about a pivot increasing the blade pitch angle and decreasing angle of attack of the blade airfoil to the wind steam. Maheswari and Tamilvendhan (2012) in their work showed that it is not always possible, to obtain rated conditions for a wind turbine. Therefore, it becomes necessary to control the wind turbine in order to increase energy production and realize a long lifetime. The control should be such that it can instantly convert the energy in the wind between, the rated wind speed (cut-in and cut-out) in proportion to speed of the rotor. Generator power output depends on rotational speed of the rotor between cut-in and rated wind speed of the turbine as in Figure 6. Due to response of the control mechanism, rotor speed and generator power output were kept constant at 100 RPM and 50 Watts respectively up to cut-out or ultimate wind speed of 8.9 m/s. At 9 m/s there exists a subsequent shutdown of the turbine by the control mechanism. The turbine starts up again with drop in wind speed. Here, the response indicates that the control mechanism was effective.

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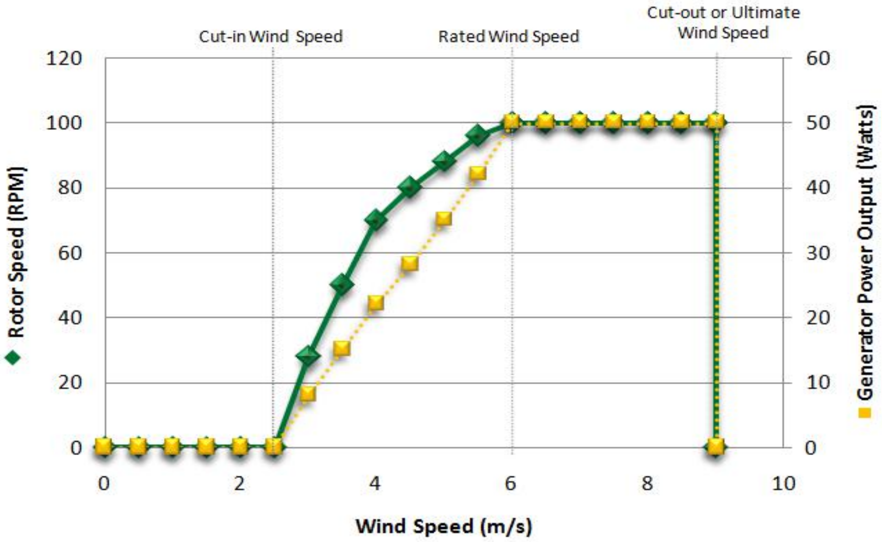

Figure 6: Generator responses to increase in wind and rotor speeds

According to Maheswari and Tamilvendhan (2012) and Soriano et al (2013) a control can only be effective if it can respond quickly and effectively for any changes in the wind speeds, so as to keep the turbine operation within its safe rated range. The result in Figure 6 shows that the control system only allows the turbine to operate between 2.5 m/s and 9 m/s cut-in and cut-out wind speeds respectively.

4. Conclusion

In conclusion the result shows that 2.5 m/s was the cut-in wind speed of the HAWT model and at 3 m/s rotor speed has reached 35 RPM with generator power output of 15 Watts. The HAWT blade pitch control mechanism has propitiously controlled the turbine to steadiness between rated wind speed of 6 m/s and cut-out wind speed of 9 m/s. Rotor speed and generator power output between these wind speeds are steady at 100 RPM and 50 Watts respectively. The cut-out wind speed of the turbine has been established to be 9 m/s at a change in governor height of 8 mm, at this wind speed the control mechanism shutdown the turbine to protect it from wind speed above 9 m/s considered high for this model design. This has been achieved because of the ability of the control mechanism to gradually change the blade pitch angle from 82 to 90 degrees deflecting the blade from the wind in other to control the turbine rotor speed. However, cut-out wind speed could be increased in further designs of prototype models for better performance under real environmental conditions.

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