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Measurement and Performance Evaluation 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. This depends on the magnitude of the wind speed that will be subjected to the turbine. A scale down of 1:10 blade geometry as designed and developed by the Author's previous work was used for the HAWT model. The HAWT model performance was tested in a wind tunnel that was developed specifically in order to carry out the experimental test. Parameters measured are the generator output voltage and rotor speed, which were based on the wind speed that was also regulated accordingly. The experimental test carried out shows that between cut-in and cut-out wind speed of 2 and 4 m/s, both the generator output, voltage and rotor speed increases with increase in wind speed. But as the wind speed increases beyond the cut-out wind speed generator output voltage and the rotor speed, there was stability and constant values were observed up to the ultimate wind speed of 6 m/s and subsequently there was a shutdown. This tested performance predicts that the variable blade pitch control mechanism will regulate and bring the require control of HAWT under high wind speeds.

Keywords: Horizontal axis wind turbine, blade pitch control, wind speed, rotor speed, generator power output

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I. INTRODUCTION

Wind is a form free-flowing green energy caused by the uneven heating of the atmosphere by 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 Turbines (HAWT) are generally with the advantage of having low cut-in wind speed, easy furling and relatively high power coefficient(Daminia and Petal, 2013). HAWT are rotor dynamic machines that are used to capture part of the kinetic energy (KE) in the wind and convert same to other forms of useful energy (electricity). To achieve this, the wind turbine is subjected to certain environmental conditions that are stochastictypical of a high wind speed phenomena are sometimes disastrous to the machine(Shuwa et al. 2015). For this reason, the needs to develop simple device that will protect the turbine under high wind speed condition is essential and should be innovated and incorporated.

Also shown to be Horizontal Axis Wind Turbine (HAWT) major drawbacks are the potential risk of generator burnout, rotor or tower failure as the wind speed exceeds it critical limit. While power is being captured from the wind by the HAWT, it is desired that the wind turbine be made to 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 wind turbine by employing pitch control mechanisms as Figure 1 shows, it involves the use of centrifugal regulators to control and monitor the blade pitch angle based on the wind speed magnitude(Chen et al, 2014).

The pitch control mechanism could be the Active Pitch Control (APC); for which 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. The other pitch control type is the Passive or Stall Pitch Control (PPC or SPC);the type of design whereby the blade does not rotate around its longitudinal axis.Its designed naturally creates a stall and lower rotation speed of the rotor. Also, it requires structurally strong towers andthat the blade is precise in its design.This is an additional expense on the total cost of the turbine(Maheswari and Tamilvendhan, 2012).

This work applies the principle of a simple mechanical watt governor in order to regulate the blade pitch angle of the HAWT, which depends, on the magnitude of the wind speed that 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; wattgovernors 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 wind speed of a three blades HAWT model, the blades was designed and developed by Shuwa et al (2015).

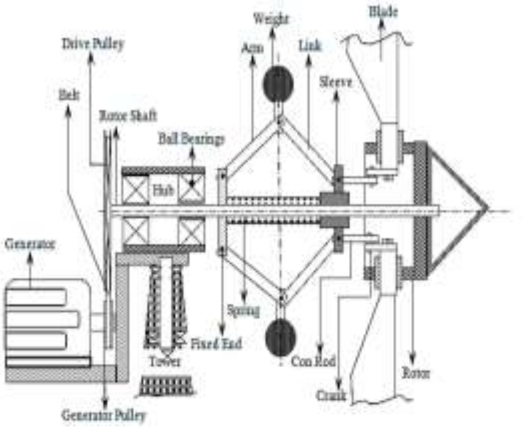

Figure 1 Blade pitch angle control mechanism on the HAWT rotor

II. METHODOLOGY

A horizontal axis wind turbine blade geometry developed by Shuwa et al (2015) is scaled down to 1:10 based on the principle of dimensional analysis and similitude and adopted for this work. A watt governor was used to regulate the blade pitch angle ofthe HAWT model. The modelwas tested in a wind tunnel at the Department of Mechanical Engineering, University of Maiduguri, which was in order to determine the speed of the rotor and the corresponding generator output voltage at a predetermined wind speed to establish the cut-in and cut-out wind speed of the turbine.

2.1 The HAWT Blade

The blade geometry developed by Shuwa et al (2015) for the micro HAWT was adopted for the HAWT model used in this work. The geometry was scaled down to 1:10 as shown in Table 1

.**Table 1** Adopted HAWT Blade Parameters and their Specifications

PARAMETER	**SPECIFICATION**	**SCALED DOWN SPECIFICATION**
Chord Length (C), m	0.26	0.026
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
Power Coefficient (CP)	0.189	0.189
Turbine Theoretical Efficiency (η), %	32	32
Ultimate Wind Speed (v_{ulti}.), m/s	8.81	8.81

2.2 The Blade Pitch Angle Control Mechanism

The HAWT is controlled at the region of the blade by regulating its pitch angle with centrifugal (or watt) governor fixedas the control mechanism. The design of the governor that helps in regulating the blade pitch angle of the HAWT are mainly to determine the minimum and maximum speed (N_1 and N_2) of the governor, as in Figure 2. The N_1 occurs when the sleeve is at its rest or initial position, while the N_2 is when the sleeve is at its maximum travel position. However the position of the sleeve (h_1 and h_2) from the fixed end (A) at the two speeds is a factor of determining the two speed limits of the governor (see Figure 2). The distance h_1 when the governor is at N_1 is determined from Equation 1, while the distance h_2 at the N_2 is determined from Equation 2 (Navathale et al, 2017).

$$h_1 = BB^1 \cdot \cos \beta_1 \quad (1)$$

and

$$h_2 = h_1 - S_T \quad (2)$$

Where: BB^1 is the Link length in mm, while β_1 is the angle between the link BB^1 and the horizontal line Bg of Figure 2 and S_T is the sleeve travel from point B to C of Figure 2

The minimum and maximum speed of the governor: speed at which the blade is at full pitch and when it is at no pitch angle are determined from Equation 3 and 4 respectively.

$$N_1 = \frac{895}{h_1 - B^1F} \quad (3)$$

Where: B^1F is the length of the link that connect the weight as shown in Figure 1

$$N_2 = \frac{895}{h_2} \quad (4)$$

With N_1 and N_2 of the governor, the pitch or angle of attack that the airfoil presents to the wind is regulated and hence the spring in the system operates the mechanism. The higher the wind speed the higher the rotational speed of the rotor, this generates a centrifugal force on the three equal mass regulating balanced weights, which compresses the spring, as shown in Figure 2. The force of the weights rotates the blade about the pivot, thereby decreasing the angle of attack of the airfoil to the wind stream by also reducing the rotational speed, stabilizing power production and protecting the HAWT. The compressed spring restores the blade to its original angle of attack gradually, as the wind speed decreases. The spring rate, K and deflection of the spring under the force, F_s are determined from Equation 5 and 6, respectively.

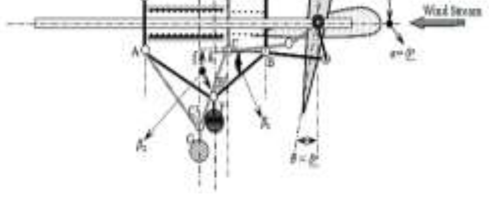

Figure 2 Section of the blade pitch angle control mechanism

The compressed spring restores the blade to its original angle of attack gradually as the wind speed decreases. The deflection, δ of the spring under F_s and K are also determined from Equation 5 and 6.

$$\delta = \frac{8F_sND^3}{Gd^4} \quad (5)$$

$$K = \frac{Gd^4}{8ND^3} \quad (6)$$

Where: G is the modulus of elasticity, D is the spring coil diameter, d is the wire diameter, N is the number of spring active turns and C is the spring index given by D/d . The applied force F_s is the centrifugal force generated by the weights as a result of the aerodynamic forces exerted by the wind on the blade, which reflect to the speed of the rotor assembly shown in Figure 1.

2.3 Experimental Test in the Wind Tunnel

The Horizontal Axis Wind Turbine (HAWT) model developed with the adopted blade and the blade pitch control mechanism was tested for performance in the wind tunnel shown in Figure 3. The wind turbine was subjected to a range of aerodynamic forces as a result of the variable wind speeds profile generated in the tunnel. The generator output voltage and rotor speed were the recorded as the turbine is subjected to the range of wind speeds. The descriptive detail of the wind tunnel in terms of its size and capacity alongside the types of instrument used are shown in Table 2.

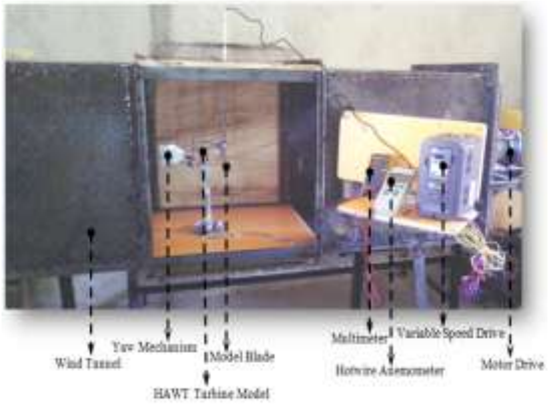

Figure 3 The experimental equipment of the wind tunnel and their assembly

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

S/No.	NAME OF INSTRUMENT	MODEL	SPECIFICATION
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

III. THE EXPERIMENTAL RESULTS AND DISCUSSION

The HAWT model tests were carried out in a wind tunnel at the Department of Mechanical Engineering, University of Maiduguri Nigeria. Figure 4 show the generator output voltage as generated by the HAWT model under certain variation of wind speeds and Figure 5 show the speed of the rotor under different wind speeds. This wind tunnel experiment was meant to estimate the performance of the turbine, with respect to wind speeds that were categorizedunder the generator output voltage and rotor speed criteria. The experiment carried out, shows that between cut-in and cut-out wind speeds of 2 m/s and 4 m/s, the generator output voltage and rotor speed increases with increase in wind speed.But as the wind speed increases beyond the cut-out wind speed, the generator output voltage and the rotor speed indicates constant value and as the wind turbine reaches the ultimate wind speed value of 6 m/s, there existsa subsequent shutdown. This indication, clearly reveals that the variable blade pitch control mechanism, have the potential and ability to regulate and bring the require HAWT control under high wind speeds based on the design parameters shown in Table 3.

Table 3 Design Parameters of the blade pitch control mechanism

PARAMETER	VALUE
Governor’s Minimum Height (h_1), mm	17.32
Governor’s Maximum Height (h_2), mm	13
Governor’s Minimum Speed (N_1), rpm	72.65
Governor’s Maximum Speed (N_2), rpm	95.58
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

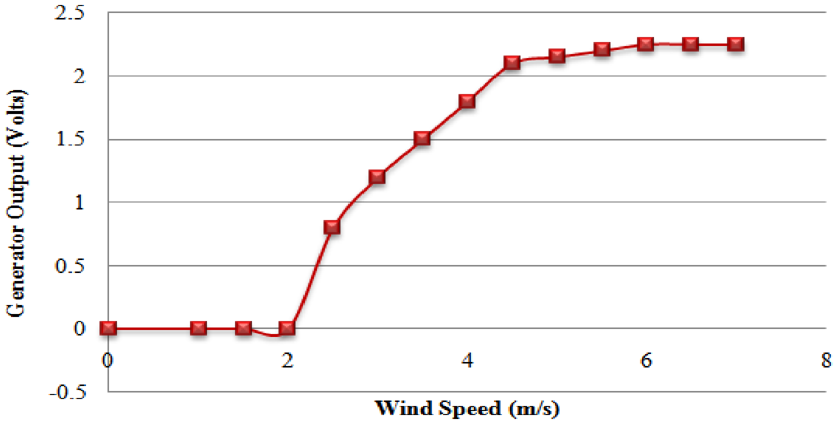

Figure 4 The Influence of HAWT generator output power on varied wind speed

3.1 Generator Output Power

The pitch control mechanism has a maximum sleeve travel length ($h_1 - h_2$) of 4.32 mm at the rotor cut-out speed of 100 rpm. At this rotor speed the mechanism rotates the blade about a pivot decreasing the angle of attack of the airfoil to the wind steam, reducing its rotational speed and stabilizing the generator output voltage as shown in

Figure 4 and 5. 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. The rotational speed of the rotor produces the generator output voltage by keeping it stable, until the wind instant speed goes beyond the rated wind speed (cut-out) as shown in Figure 6. Here, the response indicates that the control mechanism is effective. According to 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.

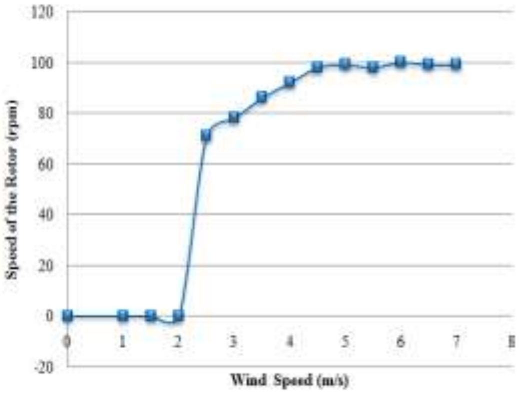

Figure 5 The effects of the HAWT rotor speed on varied wind speed

3.2 Speed of the Rotor

Also shown in Figures 4 and 5 was that the cut-in wind speed of the wind turbine model is 2 m/s, while 4 m/s is the cut-out wind speed with corresponding generator output voltage of 0.8 volts and 2.25 volts and rotor speed of 71 and 100 rpm, respectively. Between the cut-in and cut-out wind speed, the generator output voltage and the rotor speed increases with increase in wind speed and the two variables are proportional to the wind speed until after the cut-out wind speed is reached. Also, Chan and Shiah (2016) revealed that an effective control mechanism shall be able control the blade pitch angle based on their rotational speed at the rotor and magnitude of the wind speed. Similarly, the current test results showed that the generator output voltage depends on the rotational speed of the rotor, as in Figure 6. Between 0 to 71 rpm, the generation of voltage is gradual compared to the rotor speed; it becomes proportional to the rotor speed beyond 71 up to 100 rpm. The generator output voltage becomes stabilized at 2.25 volts and at beyond 100 rpm of the rotor, because the cut-out wind speed is reached and the control mechanism prove to be effective after such.

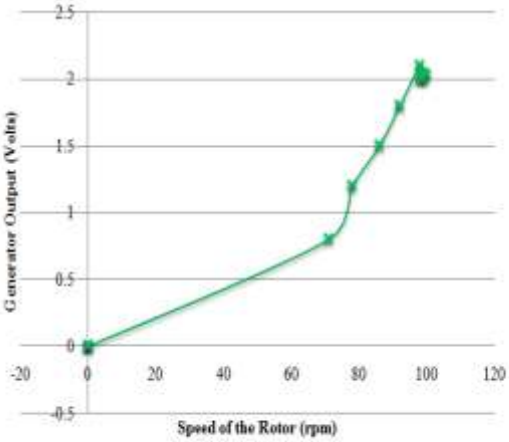

Figure 6 The variation of HAWT generator output power with turbine rotor speed

IV. CONCLUSION

Experimentally, the results indicate that the HAWT blade pitch control mechanism performance was adequate and can function in wind turbine. It can be protected at wind speeds higher than the rated wind speed, however a prototype of the model could be better off under real environmental condition and its development and effective tests is importantfor optimum performance, which is also expected to produce real result.

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