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Assessment of Aerodynamic Performance of Three Blade Savonius Vertical Axis Wind Turbine with Improved Plastic Gear System

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Abstract

The aerodynamic performance of three blades Savonius vertical axis wind turbine designed with an improved plastic gear system was investigated. The bladeseach 40cm long and 19 cm in diameter were crossflexed on the frame rods at an angle of 120^0 to each other. The model was positioned at an altitude of 542m above sea level, and wind tunnel simulations were used to measure the power coefficients ofthese blades. The results indicate that the wind speed of about 19.6 ms^{-1} was sufficient to harness the energy, generating almost 512watts and 270 watts for the upstream and downstream respectively.This low speed matches appreciablywith the use of cowling which requires a speed of 27.7 ms^{-1} and generating 520 Watts and 255.3 Watts for the upstream and downstream respectively.

Key words: Renewable energy, Wind energy, Vertical axis wind turbine, Rotor shaft, Plastic gear.

1.0 Introduction

The production and provision of electricity, is a prerequisite for technological development, economic growth, and prosperity of any nation. Nigeria is endowed with abundant human and natural resources, but there is very low provision of electricity particularly for businesses and the industrial sector due to the severe power crisis despite the enormous resources. This low or lack of access to energy for most services has led to the collapse of many industries and has led to poor participation of the private sector in the productive sector of the economy. Much of the global energy supply comes from coal, oil, natural gas, and or nuclear. Coal, oil, and gas are non-renewable. In fact, the world's natural gas, crude oil and coal deposits took millions of years to form and their intensive use is fast eroding the deposits. Uranium, which is used for nuclear energy, has limited supply as well though the nuclear energy process is somewhat considered as renewable. Once they are gone, the non-renewable energy supplies cannot be replaced within human time scales. Renewable energy on the other hand quickly replaces itself and is usually replenishable. Renewable energy comes from the natural flow of sunlight, wind, and or water around the Earth. With the help of special collectors, this energy can be captured and put to use in our homes and businesses. As long as sunlight, water and wind continue to flow and trees and other plants continue to grow, we have access to a ready supply of energy. These Renewable energy resources, if properly harnessed have the potential of meeting the world's energy demand and here in Nigeria, it can turn the economy around to address our socioeconomic problems.
Renewables are an almost unlimited source of energy if one considers the huge amount of energy we receive from the sun. Gradually renewable energy and its different energy conversion technologies have become economically viable, capable of competing with fossil-fuelled technologies in the energy market. The size and economic potential of the renewable energyresources such as solar energy, wind power, biomass and hydro are enormous in Nigeria. However, our capacity and determination to harness the renewable energy resources is presently very low. Although investment costs of renewables are generally higher compared to fossil fuel alternatives, this option becomes economically viable when all externalities (e.g. environmental cost, health hazards etc.) and lower operating cost are taken into consideration.
Among the renewable energy sources, wind energy is such a promising option due to its simple technology. Wind is a natural phenomenon related to the movement of air masses caused primarily by the differential solar heating of the earth's surface [1]. Wind is a typical example of a stochastic variable; due to this stochastic nature. Wind energy cannot be controlled, but can be managed. This is because wind power is available only when the wind speed is above a certain threshold[2].The main advantages of electricity generation from renewable energy sources, such as wind, are the absence of harmful emissions, very

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clean and almost infinite availability of wind that is converted into electricity [3]. Wind generation has been described to be one of the mature and cost effective resources among different renewable energy technologies [4].
Various models of wind turbines for generation of wind energy are gaining prominence due to the advantages of wind energy such as low cost, easy installation and maintenance. The principle of the wind-energy conversion system can be classified on the basis whether they depend on aerodynamic drag or aerodynamic lift. The drag principle was used by the early Persian VAWT wheels that have a very low power coefficient (C_P) with a C_P, maximum of around 0.16 only. However, the modern wind turbines are predominantly based on the aerodynamic lift [5].
Although the vertical axis wind turbine (VAWT) was the first ever wind turbine to be used for harnessing wind energy, researchers of the modern era lost interest in it due to the initial perception that VAWT cannot be used for large scale electricity generation. But, a closer look on the conceptsleads towards the fact that VAWTs are suitable for electricity generation in the conditions where traditional horizontal axis wind turbine(HAWT) are unable to give reasonable efficiencies such as high wind velocities and turbulent wind flows. Another major advantage is that VAWTs areomni-directional, accepting wind from any direction without any yawing mechanism [5].
Therefore, this work was conducted to design and study the aerodynamic performance of three blades savonius vertical axis wind turbine (VAWT)using plastics gear to improve rotor blades speedas part of the current drive towards the production and utilization of wind energy technology in Nigeria.

2.0 Theoretical Background

The theoretical energy possessed by the wind flowing at a certain velocity can be expressed mathematically as;

Energy $=Pt = \frac{1}{2}\rho S v^3$ (1)

The performance of the Savonius wind turbine is determined by the coefficient of performance (C_p). It is theoretically defined as the ratio of the aerodynamic power generated by the wind turbine to the power possessed by the wind incoming on the surface of the rotor.

$C_p = \frac{P}{W}$ (2)

2.1 Design of the Blades

The determination of the number of blades involves design considerations of aerodynamic efficiency, component costs, system reliability and esthetics. In the 1980s and early 1990s, attempts are made to commercialize one and two bladed wind turbine design; however, most of the modern wind turbines have three blades. The single bladed design is the most structurally efficient forthe rotor blade as it has the greatest blade section dimensions with all the installed blade surface area in a single beam [7, 3].
The experiments conducted by Gorelov and Krivospitsky [8]show that the assembly exhibits self-start at a 'sufficiently number of blades' which is given by the equation,

$N = \frac{BD}{\sigma}$ (3)

Where 'B' is the blade thickness, 'D' is the rotor diameter and 'σ' is a constant whose value is 0.28 for maximum value of C_P (0.4 approx.).
However, with a counter weight to balance the rotor statically, efficiency is reduced and complex dynamics is required for a blade hinge to relieve loads. With Aerodynamic efficiency increases the increase of the number of blades but diminishes return. Increasing the number of blades from one to two yields a 6% increase in aerodynamic efficiency, while increasing from two to three yields only an additional 3% efficiency [9, 8]. The decisive factor in eliminating one and two bladed wind turbine from the commercial market has been the visual impact. Like many design considerations, the number of blades on a wind turbine is a compromise. Three blades give a good compromise, not too much air disturbance for the following blade, and a reasonable amount of energy gathered from the airflow and delivered to the electrical generator atop the mast [9].
The wind speed passing through the turbine rotor is considered uniform and can be either upstream or downstream at a distance from the rotor. Extraction of mechanical energy by the rotor occurs by reducing the kinetic energy of the air stream from upwind to downwind. Consequently the air stream cross sectional area increases from upstream of the turbine to the downstream location.
Using Euler's theorem, the force exerted by the wind in the rotor is given by Eqn.4 as;

$F = \rho S v(v_1 - v_2)$ (4)

where;
$\rho =$ The density of air (1.26kgm^{-3}),
$S =$The cross section of the rotor blade,
$v =$The average velocity of the wind
The cross section area, S, of the rotor blade is given by:

$S = \pi r h$ (5)

The torque induced in the blade is given by:

$$\tau = \frac{2\kappa\rho U}{B} \quad (6)$$

where; τ = the stress induced (torque) in the rotor blades
κ = the kinematics viscosity(2.5×10^4),
ρ = the density of air,
B = the thickness of the blade,
U = the velocity on boundary layer.

Power extract by the blade is given by

$$P = \frac{1}{4}\rho S v^3 (1 - b^2)(1 + b) \quad (7)$$

where; S = cross sectional area,v= the free stream speed,ρ = the density of the air,
b = interference factor.
The kinetic power content of the undisturbed upstream wind is also expressed as:

$$W = \frac{1}{2}\rho S \quad (8)$$

The rotor Tip Speed Ratio, TSR depends on the blade airfoil profile used, the number of blades, and the type of wind turbine. The tip speed ratio, TSR, is dimensionless factor and is defined by

$$TSR = \frac{Speed\ of\ rotor\ tip}{Wind\ speed} = \frac{\omega r}{v} \quad (9)$$

Where:
ω = angular frequency, r = radius of the rotor,v = the velocity of the wind.
The optimal TSR for maximum power extraction is inferred by relating the time taken for the disturbed wind to reestablish itself $t_w$to the time required for the next blade to move into the location of the preceding bladet_b.
If $t_s > t_w$, some wind is unaffected. If $t_w > t_s$, some wind is not allowed to flow through the rotor. The maximum power extraction occurs when the two times are approximately equal.

3.0 Methodology

The simple model construction of the blades is shown in Fig. 1.

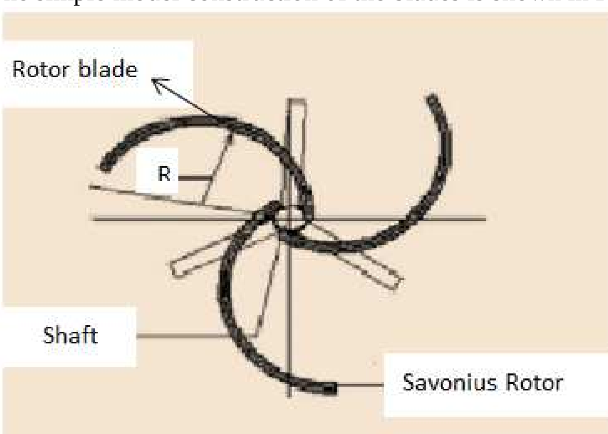


Fig. 1: Three blades VAWT schematic

The blade is 40cm long and 19cm in diameter. Since, the blades were cross flexed on the frame; they are at angle of 120^0 to each other. The thickness of the blades was found as $B = 0.012mm$. Also the cross section area, S, of the rotor blade is given as $S = 0.1194m^2$ Approx.

Theconstructed rotor blades, the shaft of the rotor in the magnetic field region and plastic gear used to move the rotor faster are shown in Fig. 2.

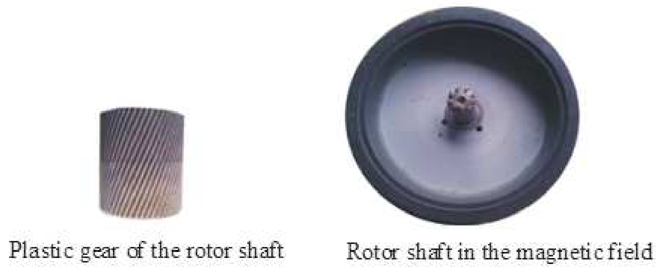


Fig. 2: Constructed Plastic gear and Rotor shaft

Furthermore, after assembling the above materials in order to make the generator workable, the complete construction of the rotor blade is shown in the Fig. 3.

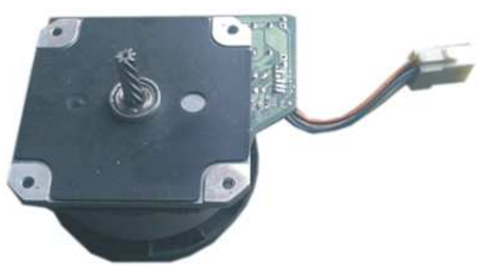


Fig. 3: The constructed rotor blade

In order to generate electricity the shaft of the turbine must be connected to an electrical generator. Through gearboxes, the generator converts the mechanical energy of the spinning turbine shaft into electricity. Generators are small and light enough that they can be housed under an aerodynamically designed cover at the top of the pole or tower. Wires running down the tower carry electricity to the grid, batteries or other appliances, where it is stored, and/or used

The complete constructedSavonius three blades vertical axis wind turbine was placed at an altitude of 542m above the sea level. The mechanical power for the constructed Savonius three blades vertical axis wind turbine was determined by measuring thewind speed at the upstream and the downstream of the blades usingpropeller type digital anemometer. The speed and temperature of the wind around the blades were measured using digital thermometer daily for two months.

4.0 Results and Discussion

The mean free stream velocity was plotted against the TSR as shown in Fig. 4 Small TSR is shown to favour higher free stream velocity for both the upstream and downstream settings.

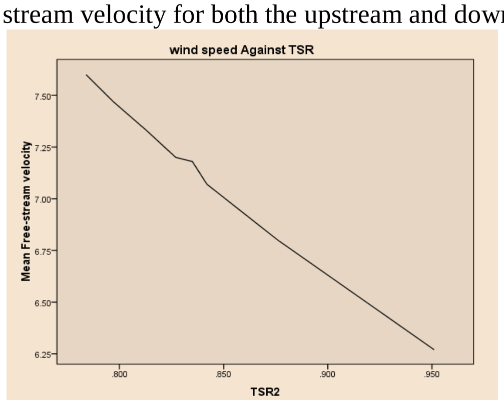
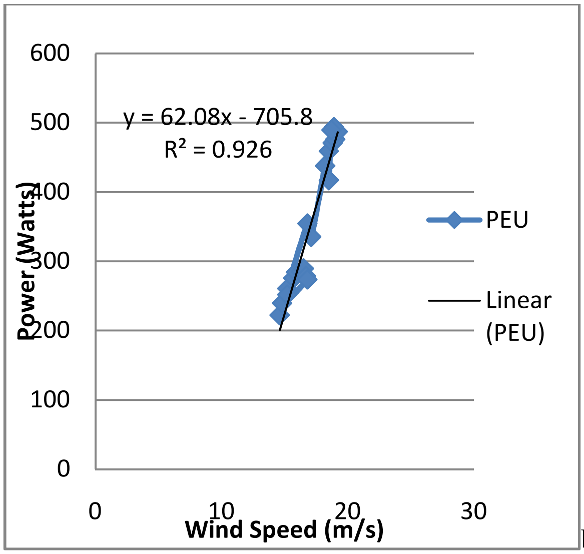


Fig. 4: Plot of wind speed against TSR

The mechanical power extracted for the upstream and downstream was plotted against wind speed as shown in Fig. 5The largest mechanical power were found to occur with wind speeds between 18 m/s and 20 m/s, while the lowest were found to occur at wind speed less than 15 m/s. The power was seen to relate linearly with the wind speed with a peak of about 512 W for the upstream and 270 W for the downstream.

a. 

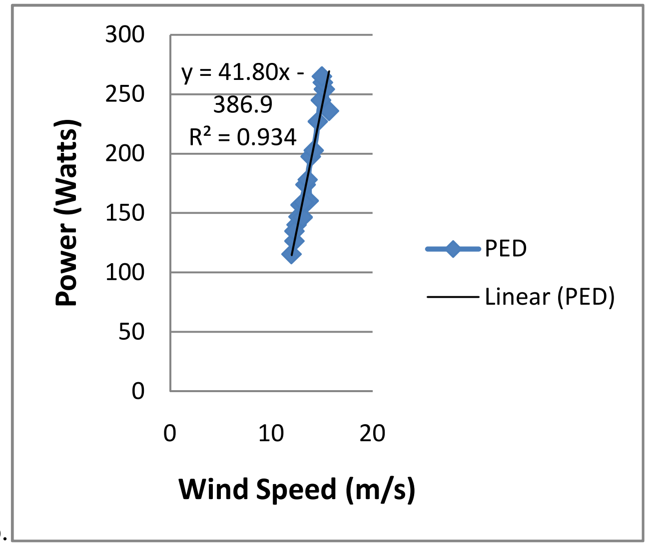
b. 

Fig. 5 (a) and (b): Relationship between the Mechanical Power and the Wind Speed (Upstream and downstream) of three blades vertical axis wind turbines.

The free stream velocities were plotted against tip-speed ratios in Figures 4. It can be observed that the coefficient of performance of the upstream and the downstream increases as the tip-speed ratio increases until a critical tip-speed ratio is reached; performance decreases for higher tip-speed ratios. The largest coefficients of performance were found to occur with tip-speed ratios between 0.8 and 1.1, depending on the stream. It was also observed that for subcritical tip-speed ratios, the variation of the coefficients of performance across different turbines was smaller; the fluctuation was observed in the data above the critical ratio and it increased with increasing ratios. These data further suggest that, when turbines operate at their highest rotational speeds, the scatter in both the subcritical and supercritical regions is reduced considerably. However, the range of tip-speed ratios that yield very good performance is wider in this case, suggesting that the reliability of performance is less sensitive to small changes in wind speeds.

Figure 5 (a and b) shows the actual power produced at various wind speeds by a three blades vertical axis wind turbine with plastic gear system. There is highly significant and positive correlationbetween the mechanical power and wind speed of the upstream and downstream respectively.

The results suggested how plastic gear system can enhance the performance of VAWT that operate at low speed ratios between 18m/s to 20m/s, other than those that suffer from detrimental dynamic stall effect, like cowling [11]. Firstly, gearing increase the blades torque coefficient which would result in more energy extracted from the flow and increased power generated by the turbine.

In practical applicationofthe plastic gear system, the height at which the turbine is placed is alsooneofthedesignparameters.Forthestudy on theinfluenceofthe gearing on poweroutput,we considered a downstream flow height of 6m. For the upstream flow the height was 12m, as the windis blown onlyaroundtwosideedgesofthe blades. However, forthe downstream,the free-stream velocity of the wind flow indicates the fast movement of the tip-speed ratio of the rotor over thetopedgeofthe turbine aswellasaroundthesideedges of the blades. Thus, theincreaseinwindvelocity of the rotor speed is reduced, andthe power outputaugmentationisalsoexpectedtobereduced. Both the maximum power coefficient and the corresponding tip speed ratio were smaller than the upstream case.

5.0 Conclusion

We investigated the effect of a plastic gear system on the power output of a three-bladed savonius turbine. This system takes advantage of the simple principles that local wind velocity around the turbine could increase by the rotor speed flow and power output is proportional to the cube of the wind velocity. Power output of a turbine increases significantly if the turbine is properly positioned. For high power output increase, the turbine axis should be placed at the upstream. The height of the vertical axis wind turbine is also an important factor in power generation. Maximum power of 512 W for the upstream and minimum of 270 W for the downstream settings were obtained.

This study was limited to a specific model wind turbine of high solidity and low power coefficient. Therefore, it is necessary to study if this plastic gear concept can be applied to general lift-based vertical-axis turbines. Another issue of this gear system is that the turbine blades encounter a non-uniform wind during revolution. With a plastic gear, the unsteadiness of the local flow field and the variation of aero- dynamic loading during revolution will increase compared to general VAWTs. In order to address this issue, we plan to study the flow physics near the plastic gear and turbine as well as the effect of an upstream on aerodynamic loading of the downstream blade.

6.0 References

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