Design and Fabrication of a Vertical Axis Wind Turbine with introduction of Plastic Gear

J. K. Adebayo, A. T. Layeni, C. N. Nwaokocha, S. O. Oyedepo and S. O. Folarin.

Abstract-
This project is a design of Vertical Axis Wind Turbine using Kinetic theory, Aerodynamics model, Hooke’s law and Young Modulus. Aerodynamic model method was use to design the blade and the blades are three for effective harness of the wind speed. Bearing was introduced for easy rotation and reduction of noise. The use of plastic gears was introduced so that one revolution of the shaft carrying the blades leads to forty six (46) revolution of the alternator. The alternator then generate electric power. The power generated was 65 W under wind speed of 0.8m/s.

Key words: Solid Shaft, Blade, Alternator, Gear, Bearing and Teflon

1. Introduction
Energy is absolutely required our life. It furnishes us with make life easy, beautiful and better for us. Its enhance activities that associated with advance country like transportation, technology advancement and the ability to produce food and material goods. Energy is a fundamental ingredient for development [1], and has always been a vital and indispensable input to the economic needs of our present civilization [2]. It functions as the driving potential for industrialization.

Research shows that increase in the World population is directly proportional to increase in energy demand, therefore to meet the increasing in energy demand as a result of fast growing population in the past few decades, wind energy, as one of the renewable energy resources, is widely developed. Wind energy is free renewable energy unlike fossil fuels, coal and natural gas that pollute the environment. There is no air-pollution emission to environments after consumption of wind energy. As a result, the development of wind energy has been drawing attention from academia to industries [3].

Historically, energy has been directly related to the gross national product (Jonathan and Brian, 2016) [4], which is a measure of the market value of the total national output of goods and services. A most casual look at our civilization shows the important part played by the supply and control of energy.

Wind is a natural phenomenon that has to do with the movement of air masses caused primarily by the differential solar heating of the earth's surface. The different or variation in the energy received from the sun affects the strength and direction of the wind. The way in which aeroturbines transform energy in moving air to rotary mechanical energy suggests the use of electrical devices to convert wind energy to electricity [5]. Wind energy has been in used for decades, for water pumping as well as for the milling of grains [6].
Wind energy has now been developed into one of the major alternative energy sources. Over 159,000 [7] megawatts of wind generation were operational by the end of 2009 [8] with 38,312 megawatts added in 2009 alone [9]. The reasons for this growth are clear and straightforward. Wind is a boundless energy resource which is clean and renewable. By its integral nature, wind power has the potential to reduce the environmental impact on wildlife and human health. Improvements in power electronics, materials, and wind turbine designs allow production to continually lower the cost of wind generated electricity making it today economically viable compared with most other fossil fuels.

Vertical axis wind turbine, such as the Daurries (built in 1931) [10] use drag instead of lift. Drag is resistance to the wind, like a brick wall. The blades on vertical axis are designed to give resistance to the wind and are as a result pushed by the wind. Windmills, both vertical and horizontal axis, have a lot of uses of which some of them are: hydraulic pump, motor, air pump, oil pump, churning, creating friction, heat director, electric generator, Freon pump, and can also be used as a centrifugal pump [11].

2. Methodology
2.1 Theory

The power in the wind can be computed by using the concepts of kinetics. The wind mill works on the principle of converting kinetic energy (K.E.) of the wind to mechanical energy. The same method is used in this design. The kinetic energy of any particle is equal to one half its mass times the square of its velocity, or \( \frac{1}{2} mv^2 \). The amount of air passing in unit time through an area \( A \), with velocity \( u \), is \( AV \), and its mass ‘\( m \)’ is equal to its volume multiplied by its density \( \rho \) of air, or

\[
m = \rho AV
\]

\( m \) is the mass of air transversing the area \( A \) swept by the rotating blades of a wind mill type generator.

Substituting this value of the mass in expression of K.E.

\[
P_w = \frac{1}{2} \rho AV^3 W
\]

Where

\( P_w = \text{power of the wind (W)} \)

\( \rho = \text{air density (kg/m}^3) \)

\( A = \text{area of a segment of the wind being considered (m}^2) \)

\( V = \text{undisturbed wind speed (m/s)} \)

At standard temperature and pressure

\[
P_w = 0.613AV^3 \quad (3)
\]

\[
P_m = \frac{1}{2} \rho(16/25 AV^3) \quad (4)
\]

Where

\( P_m = \text{mechanical power (W)} \)

\[
P_m = C_P Pw
\]

Where

\( C_P = \text{coefficient of performance} \)

\( C_P = (15\% \text{ efficiency}) \) (Chang, 2005)

\[
C_P = \frac{\text{Captured Mechanical power by blade}}{\text{Available power in the wind}}
\]
2.2 Aerodynamic Model of Turbine Blade

In order to model the performance of a vertical-axis wind turbine there are four main possible approaches [6]:

Table 1. Features, advantages and shortcoming of different aerodynamic models for vertical-axis wind turbine (VAWT) rotors. (Tchakoua et. al., 2015)

| Model                        | Main features                                                                 | Advantages                                                                 | Shortcomings                                                                                   |
|------------------------------|-------------------------------------------------------------------------------|-----------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| Momentum or blade element model | Combines momentum theory with blade element theory. Uses the calculation of flow velocity through the turbine by equating the streamwise aerodynamic force on the blades with the rate of change of momentum of air. Momentum models include the single streamtube model, multiple streamtube model and Double-multiple streamtube model. | Can predict the overall performance of a lightly loaded wind turbine. It is thus useful for overall design. Very fast computational prediction. Can provide a good correlation between the performance prediction and the experimental data (double-multiple streamtube model). | Invalid for large tip speed ratios and for high rotor solidities. Does not provide any information as to the shape of the near wake, which is important when considering the placement of struts and other structures close to the turbine blades. The effect of perpendicular perturbations in blade element momentum (BEM) methods can only be added as a correction. Cannot predict wind velocity variations across the rotor. Some convergence problems (double-multiple streamtube model). |
| Vortex model                 | Potential flow models based on the calculation of the velocity field about the turbine through the influence of vorticity in the wake of the blades. Vortex models include the free-wake vortex model and fixed-wake momentum theory. | Can include the dynamic stall effect, pitching circulation and added mass effect. Capable of providing information about the wake structure near the turbine because the velocity normal to the airflow is neglected. High-precision prediction capabilities. Can be used for highly | Computationally too expensive. Relies on significant simplifications (such as the potential flow being assumed in the wake, and the effect of viscosity in the blade aerodynamics is included through empirical force coefficients). |

| **Cascade model** | Consists in equidistantly placing the blades one behind another on a plane, the width of which is the circumference of the rotor. The aerodynamic characteristics of each element of the blade are independently obtained using the local Reynolds number. Convergence problems in some cases. Computational accuracy greatly dependent on the potential flow model used in computations. Reasonable computation time. |
| **Computational fluid dynamics (CFD) model** | CFD simulation of VAWT is performed by solving the Unsteady Reynolds Averaged Navier Stokes (URANS) equation. According to the discrete principle, CFD models can be generally classified into three branches: the Finite Difference Method. Provides a more precise aerodynamic prediction for VAWTs (reliability and accuracy). Can visualize the flow near airfoils in detail. Can accelerate the design process and reduce the overall cost of design. Computationally intensive. Basically prohibitive for the routine engineering analyses of wind turbines. |
(FDM), the Finite Element Method (FEM) and the Finite Volume Method (FVM).

Effective solutions for the analysis of local flow fields around blades, particularly for dynamic stall and wake flow. Attractive solution for performance optimization.

Figure 1: Detailed airfoil (daviddarling.info)

Figure 2: Blade profile of the wind turbine

The induced velocity in the upstream part of the rotor is:

\[ V_u = V_0 au \]  \hspace{1cm} (6)

Where \( V_u \) is the upstream induced velocity, \( V_0 \) is the free stream air velocity and \( au \) is the upstream interference factor, which is less than 1 as the induced velocity is less than the ambient velocity.

In the middle plane between the upstream and downstream there is an equilibrium-induced velocity \( V_e \):

\[ V_e = V_0 (2au - 1) \]  \hspace{1cm} (7)

The downstream part of the rotor, the corresponding induced velocity is:

\[ V_d = V_e \cdot ad \]  \hspace{1cm} (8)
Where $V_a$ is the downstream induced velocity and is the downstream interference factor which is smaller than the upstream interference factor.

The resultant air velocity that the blade sees is dependent on the induced velocity and the local tip speed ratio:

$$W_u = \sqrt{V_u^2[(TSR - \sin^2\theta)^2 + (\cos^2\theta)]}$$

(9)

Where $W_u$ is the resultant air velocity and TSR is the local tip speed ratio defined as:

$$TSR = R \frac{\omega}{V_u}$$

(10)

Where $R$ is the rotor radius and $\omega$ is the angular speed.

2.3 Pictorial and Exploded View of Wind Turbine

Figure 3 Exploded View
2.4 Arrangement of Gear

The turbine is made of speed multiplication spur gear with the ratio of 1:47 (Khurmi, 2005)

![Figure 5: Gear Arrangement](image)

A- Pinion (gear attached to the shaft and B is the driven or gear.

For pinion, \( P_c = \frac{\pi D_A T_A}{T} \)

\[
P_c = \frac{\pi \times 278}{160} = 3.142 \times 278 = \frac{160}{160}
\]
For gear C and D

\[ D_D = 40\text{mm} \quad T_D = 21 \]

\[ P_C = \frac{\pi D_D}{T_D} = 5.98 \]

\[ P_C = \frac{T_C}{T_D} = \frac{D_C}{D_D} \]

\[ 5.98 = \frac{21}{T_C} \]

\[ T_C = 140 \]

\[ D_C = 270\text{mm} \]

Module for gear A is \( \frac{D}{T} = 1.74\text{mm} \)

Tangential load on the gear tooth ‘\( W_T \)’

\[ P \times C_S \]

\[ P = \text{Mechanical power, } v = \text{Pitch line velocity in m/s and } C_S = \text{service factor.} \]

\[ P = 774.4\text{N, } C_S = 1.25 \]

Taking \( N \) to be 500 r.p.m.

\[ = 7.26\text{m/s} \]

\[ W_T = \frac{774.4}{7.28} \times 1.25 = 132.97\text{N} \]

Normal load acting between the tooth surfaces ‘\( W_N \)’

\[ W_N = \frac{W_T}{\cos \theta} = \frac{132.97}{\cos 20^\circ} \]

141.5N

Weight of the pinion \( W_G = 0.00118T_Gb m^2 \)

Where \( b = \text{face width} = \frac{W_T}{(\sigma_{OP}C_p\pi)_{\text{rpm}}} \)

\[ \gamma_p = 0.154 - \frac{0.912}{T_A} = 0.1483 \]

Taking \( \sigma_{OP} = 42\text{MPa} = 42\text{N/mm}^2 \)

\[ b = 11.47 \]

\[ W_G = 0.00118 \times T_G \times b \times m^2 = 6.56\text{N} \]

Resultant load acting on the gear \( W_R \)

\[ = \sqrt{(W_N)^2 + (W_G)^2 + 2W_N \times W_G \cos \theta} \]

\[ \sqrt{(141.5)^2 + (6.56)^2 + 2 \times 141.5 \times 6.56 \times \cos 20} \]
2.5 Design of Shaft

In the design of shaft, stiffness and torsional rigidity consideration was taken into account. Insufficient rigidity can result in poor performance. The ASME code equation for a solid shaft having little or no axial loading is given as:

\[ T = \frac{42N/mm^2}{\pi N} \]

Where, \( d \) = shaft diameter, mm; \( M \) = bending moment, Nmm; \( T \) = twisting moment, Nmm; \( K_b \) = Shock and fatigue factor for bending moment and \( K_t \) = shock and fatigue factor for twisting moment. For the gradually applied load or rotational shaft \( K_b = 1.5 \) and \( K_t = 1.0 \)

Therefore \( T = \frac{7444 \times 60}{2 \pi \times 1500} \) Nmm = 3.6975Nmm and \( M = \frac{35 \times 700}{4} \) Nmm = 6125Nmm

Equivalent twisting moment

\[ T_e = \frac{(K_m \times M)^2 + (K_t \times T)^2}{2 \pi N} \]

\[ T_e = \sqrt{(1.5 \times 6125)^2 + (1 \times 3.6975)^2} \]

\[ 9187.5004 \text{ Nmm} \]

\[ d = \frac{16 \times 42 \times d_s^3}{n} \]

\[ d = 11.87 \text{ mm} \]

Therefore the diameter of the shaft is 12mm.

![Figure 6 Gear attached to Shaft](image)

Twisting moment \( T \) of the shaft as a result of gear attached to it.

\[ W_T \times \frac{D_c}{2} \times 132.97 \times 0.278/2 \]
3. Result and discussions

3.1 Performance Test

Average Generated voltage = 38V
Average Electrical power = 65W

Figure 7: The effect of wind speed on power output

Figure 8: The effect of Turbine (rotor) diameter on power output
3.2 Discussion
The result obtained shows that in some region of low wind speed, there is a way wind energy can be harnessed using small scale wind turbine and gear mechanism to produce an encouraging voltage and power. This design produces an average direct voltage of 38v and Electric power of 65W. It shows that this can be improved to get desirable electric power output.
It was discovered that wind speed and area of rotor are major parameters that affect both wind power harnessed and Mechanical power. Also the blade shape (aerodynamic of blade) determine effectiveness of the blade to harnessed wind speed. The wind speed is amplified by the introduction of plastic spur gear in the base. The spur gear help to multiply rotational speed caused by wind speed. This shows that in area or region where there is no powerful wind speed, this method can be used to maximize the available wind speed harnessed and converts it to electrical power.
Figure 7 shows the effect of wind speed on the power output of the turbine at different efficiency. It was observed that at speed lower than 2 m/s the turbine appears not to produce much power, however, at speeds higher than 2 m/s the efficiency of the turbine shows major difference in power output. At wind speed of 5 m/s the power outputs per unit area were found to be 7.66, 19.14, 38.28 and 49.94 W/m² at turbine efficiencies of 10, 25, 50 and 60% respectively. From this analysis the device would not be effect in areas where average wind speed is less than 2 m/s.
The effect of turbine on the power output, as shown in Figure 8, revealed that an increase in rotor diameter shows a significant increase in power output, particularly wind speed of 5 m/s resulting in power outputs of 24.09, 60.24, 120.47 and 144.57 W at turbine efficiencies of 10, 25, 50 and 60% respectively.

4. Conclusion
The fabrication of this design shows that light materials like fiber plastic that will not add much weight to the shaft’s weight is of great help in multiplying the revolution of the alternator and in turn produce Electrical Energy. It is discovered that light weight gear boost the little wind energy that blade could harness.

5. Recommendation
Wind energy is a good source of renewable energy. It is environmental friendly and better than fossil fuel and the likes, therefore I recommend more research to be done especially in the area of using gear mechanism to increase power output.
   1. More research can be done on the best material that could be used for manufacturing of gear for this purpose.
   2. Fore work can be done on the best arrangement of gear meshing to ease the operation and maintenance.
   3. Further work can be done in such a way that some region with low wind speed such as 5m/s can benefit the use of wind energy with the introduction of gear.

Acknowledgements
I use this opportunity to acknowledge the Almighty God (giver of life) who sustained me up to this moment and my beloved wife who did not make life unbearable for me so that I have time to put this together for the success of this manuscript.
Reference

[1] Adeyemo, S.B. (2001) – Energy potentials from organic wastes: Proceedings of the First National Conference, 2nd – 3rd May, 2001. Department of Mechanical Engineering. University of Uyo, Nigeria, ISBN – 978-35533-0-5 pp 56 – 61
[2] Bernhoff, H., Eriksson, S., & Leijon, M. (2006). Evaluation of different turbine concepts for wind power. Renewable & Sustainable Energy Reviews, 12(5), 1419-1434
[3] Boyle, G. 2004, Renewable energy, power for a sustainable future, OxfordUniversity Press, Oxford, England, p. 244, p.257.
[4] Emmanuel Bergasse (2013). The relationship between energy and economic and social development in the southern Mediterranean-MEDPRO Technical Report No. 27/February 2013
[5] Emrah Kulunk (2011). Aerodynamics of Wind Turbines, Fundamental and Advanced Topics in Wind Power, Dr. Rupp Carriveau (Ed.), ISBN: 978-953-307-508-2, InTech, Available from: http://www.intechopen.com/books/fundamental-and-advanced-topics-in-wind power/aerodynamics-of-windturbines
[6] Cooper, P. (2010). Development and analysis of vertical-axis wind turbines. In W. Tong, Wind power generation and wind turbine design (pp. 289-296). WIT Press.
[7] http: // wiki.answers.com/Q/Operation of dc_generator
[8] Khurmi, R. S. and Gopta, J. K. (2005). Machine Design. Eurasia Publishing House, Ltd. Ne Delhi, India.
[9] Mitchel, John W. (1983) Energy Engineering, John Wiley and Sons.
[10] Sanbo, A. S. (2005) Renewable Energy For Rural Development: The Nigerian Perspective Energy Technologies- Nicon Hilton Hotel, Abuja 14-15 Nov. 2002, pp 1-22
[11] Shigley, J. E. and Mischke, C. R. (2001). Mechanical Engineering Design. Mc-Graw Hill Co. Inc. New York.
[12] Tchakoua Pierre, Wamkeue René, Ouhrouche Mohand, Andy Tameghe Tommy and Ekemb Gabriel, (2015). A New Approach for Modeling Darrieus-Type Vertical Axis Wind Turbine Rotors Using Electrical Equivalent Circuit Analogy: Basis of Theoretical Formulations and Model Development. Energies 2015, 8, 10684-10717; doi: 10.3390/en81010684
[13] World Wind Energy Association (March 10, 2010).World wind energy report executive report. Retrieved August 21, 2010 from http://www.wwindea.org/home/index.php
[14] Zhenyu Wang, Yuchen Wang and Mei Zhuang (2018) Improvement of the aerodynamic performance of vertical axis wind turbines with leading-edge serrations and helical blades using CFD and Taguchi method. Energy Conversion and Management 177(2018) 107-121. https://doi.org/10.1016/j.enconman.2018.09.028