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Performance Analysis of Two Different Sizes of Wind Turbine Rotors Based on Nigerian Low Wind Regime

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Abstract

Nigeria can reduce its level of dependency on fossil fuel by making use of wind energy which is an indigenous renewable energy source for electricity generation. For large energy generation, large wind turbine is more preferable over a wind farm of smaller wind turbine units that will generate the equivalent amount of energy because, there will be loss of energy due to transmission and generation system of every turbine unit of the wind farm while the larger turbine has only one transmission and generation units. However, smaller wind turbines are generally more efficient than the bigger ones in terms of wind energy conversion and they are therefore good for small power generation. In this research work the performance of two different sizes of small wind turbine rotors, a 4-metre rotor (D4-Rotor) and a 4/5-metre one (D4/5-Rotor) were studied at 6m/s wind speed using numerical method. The POINTWISE software is used for modelling the rotor blade and meshing the flow domain. The software used for the simulation is ANSYS 20 which uses finite volume method (FVM) of analysis for solving governing flow equations. From the result of performances, the D4/5-Rotor has higher power coefficient (0.2995) than that of D4-Rotor (0.237), and this indicate about 26 per cent performance improvement of the smaller rotor. Conclusively, smaller wind turbines are more efficient than the bigger ones in terms of wind energy conversion and they are therefore good for small power generation especially in low wind regime.

Keywords: Wind turbine, performance coefficient, wind turbine rotor, wind turbine blade, wind speed.

1.0 INTRODUCTION

Nigerian is among the countries with low power generation capacity; with available power generation likely to be constrained to just 7.6GW and this supply is far behind demand [1], despite Nigeria being the most populous country in Africa with current population 213,019,097 based on worldometer elaboration of the latest United Nation data [2]. Most of the energy source in Nigeria is from fossil fuels but however fossil fuels have some environmental and sustainability problems such as pollution as result of acid deposition, oil spillage and global warming due to green-house gas emissions. The population of Nigeria increases and the consumption of this source of energy also increases and it is a well-known fact that this source of energy is not renewable, so the need for sustainable alternative energy sources is imperative. Wind energy is one of the most significant and rapidly developing renewable energy sources all over the world. Recent technological developments, fossil fuel usage, environmental effects and continuous increase in the conventional energy resources rendered wind energy costs to economically attractive levels and consequently, wind energy farms are being considered as an alternative energy source in many countries. Wind energy is an alternative renewable clean energy to fossil fuel based energy source, which contaminates the lower layers of the troposphere. Owing to its cleanness, wind power is sought wherever possible for conversion to electricity with the hope that air pollution is reduced as a result of less fossil fuel burning.

Research works have being conducted on assessment of wind energy potentials and feasibility studies of wind energy utilization in Nigeria. Pam [3] worked on estimating wind speed probability distributions for Kano, Maiduguri, Sokoto and Zaria in Northern Nigeria. From the four locations considered in his study, the estimates from the mean wind and standard deviation method gave the best overall fit to the observed distribution. This was followed by the least-squares fit method and lastly the median and quartile wind speed method. Argungu [4] studied the wind energy resources in Nigeria for power generation. From his study, result indicated that Sokoto, Jos, Pankshin, Gembu and Kano recorded highest wind speed. Felix et al. [5] presented a wind energy potential in Nigeria. He described the wind energy in Nigeria and specified the conditions to be met

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before the wind generator can be connected to the existing grid. Ahmed et al. [6] investigated wind characteristics and techno-economic evaluation of wind energy in Nigeria.

From his study six locations (Kano, Sokoto, Maiduguri, Plateau, Lagos and Enugu) were quite viable for electricity generation using four different wind turbine models, with cost ranging between 0.493-0.606$/kWh. Ahmed and Kunya [7] investigated wind energy resource on the basis of Weibull and Rayleigh models in north eastern and western, Nigeria. The Weibull model was found to be better fit than the Rayleigh model in analyzing the wind speed data. The north western part of Nigeria was found to have higher wind power density as compared to the north eastern part of the country. Estimation of wind Energy potential for two locations (Bauchi and Maiduguri) in north-east region of Nigeria was carried out by Ahmed and Kunya [8]. Mean monthly values were used in calculation of Weibull distribution parameters c (scale factor ms-1) and k (shape factor). The Weibull results shows that for Bauchi, the shape factor ranges from 2.86 – 5.96 and scale factor ranges from 2.32ms^{-1} – 2.54ms^{-1} while Maiduguri the shape factor ranges from 2.66 – 5.52 and values of scale factor ranges from 4.74ms^{-1} – 5.89ms^{-1}.

The utilization of wind energy in Nigeria is not adequate, one of the factors that led to poor wind energy utilization despite the availability of studies on assessment of wind energy potentials and feasibility studies of wind energy utilization in the country, is lack of availability of technology specific of the configuration of wind turbine that can work more efficiently in the country's wind regime. Only few research works on wind turbine design related to wind speed condition of Nigeria have been done. Kunya et al. [9] designed, constructed and tested a 3-metre wind turbine rotor with NACA 4412 blade section profile in low wind speed of Nigeria. It was tested at 22 metre hub height and achieved an efficiency of 22.2% on the basis of projected 6.15m/s average wind speed. NACA 4412 aerofoil profile was used in the work but there is still need to test other low wind speed profiles such as some of the NASA aerofoil section profiles and testify their performances. Imhade et al [10] work on design and implementation of 0.5kw horizontal axis wind turbine for domestic use was intended for wind power generation in Nigeria but however the prevailing wind speed considered (20.9m/s) is far higher than the Nigeria average wind speeds. A numerical study of three-bladed wind turbine rotor at low wind speed was done by Kunya et al. [11] on modification of turbine rotor blades' leading edges (by introducing sinusoidal bumps). The results of their performances show that both modified (bumpy) and unmodified (smooth) rotor are good but the bumpy model is better than the smooth one in the low wind speed condition and angle of attack (6^{o}) considered; the bumps act as passive flow control devices. Around the same period of time, Major and Oshiemele [12] carried out numerical simulation on hybrid power system and the results obtained shows that wind-and-diesel hybrid power system with battery storage can be operated suitably for a more reliable power supply for fuel savings improvement. Economic analysis conducted shows the positive benefits of implementing the hybrid wind-and-diesel power system rather than continuing with the traditional diesel power plant over the project life cycle of 20 years. More recently, Samuel et al. [13] numerically studied the operational flow analysis of a proposed wind turbine model in Nigerian Defence Academy (NDA) Kaduna. They considered wind speed of 5.6m/s, 7.5m/s and 9.5m/s. The flow nature of the turbine model grew from laminar flow to turbulent flow increasingly with wind speed. The flow nature remained laminar from 0.0356 to 1780 Reynolds number (Re) at 5.6m/s. Although the incoming wind speed is the same but it changes on reaching different locations of the wind turbine and hence the differences of Re; speed at the root of wind turbine blade is lower than at the tip. At 7.5m/s wind speed, the flow nature changes from laminar (Re = 0.403) to turbulent (Re = 4290), and at 9.5m/s, it changes from laminar (Re = 0.381) to turbulent (Re = 4900). High turbulent flow and mass imbalance nature depicts that phenomenon like wake and vibration of the system occurred.7

For large energy generation, large wind turbine is more preferable over a wind farm of smaller wind turbine units that will generate the equivalent amount of energy because, there will be loss of energy due to transmission and generation system of every turbine unit of the wind farm while the larger turbine has only one transmission and generation units. However, smaller wind turbines are generally more efficient than the bigger ones in terms of wind energy conversion and they are therefore good for small power generation. In this research work two different sizes of roof top wind turbine rotors were studied. This is done to study the effect of rotor size on performance of wind turbine in terms of wind energy conversion at low wind speed condition.

2.0 METHODOLOGY

Performances of two different small sizes of wind turbine rotors were studied in this work; (i) D4-Rotor: a 4 metre three-bladed wind turbine rotor with NASA LS (1)-0413 blade section profile and, (ii) D4/5-Rotor: a 4/5 metre rotor with number of blades and blade section profile same as the first one. The former model is from the work of Kunya el al. [11] on the experimental and numerical study of the effect of sinusoidal bumps at the leading edge of a rotating wind turbine blade with NASA LS (1)-0413 cross-section profile at low Reynolds Number, while the later model has been modelled and simulated in this research work based on the same wind speed condition. The geometry of the flow domain consists of a single blade rotating through a 120º (Figure 1a). It is 4 m long with the blade placed 1m from the inlet allowing for 3 m wake development region. The POINTWISE software is used to model and create the mesh with 4.5 million unstructured cells. Figure 1b shows the dimension and meshing of the flow domain.

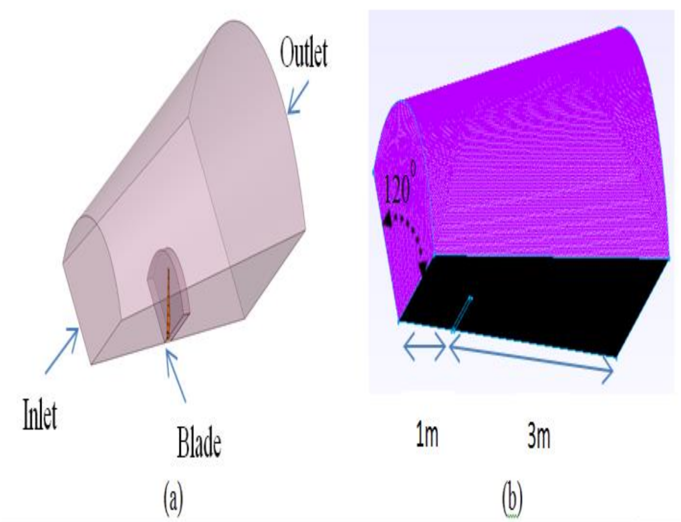

Figure 1: Diagram of the flow domain

In order to accurately capture the flow physics and to minimize computation error, the blade has mesh cells clustered near the curvature of the leading edge and trailing edge as shown in Figure 2.

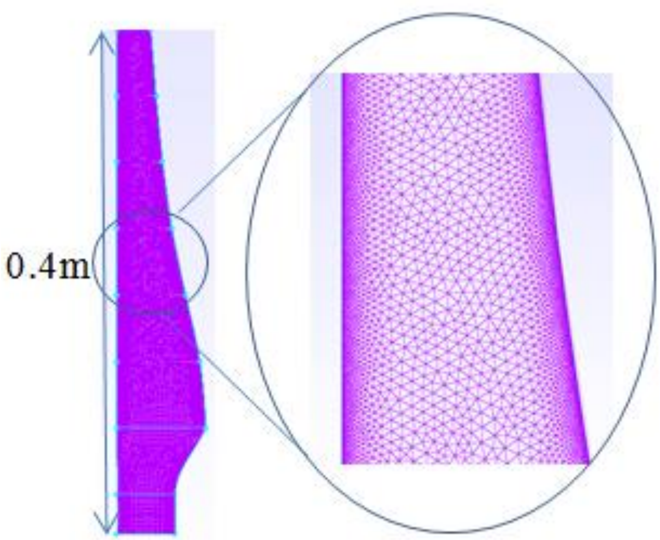

Figure 2: Meshing around the blade

Moving reference frame (MRF) method in which air is rotated around a blade rather than the blade moving in the air is used. The blade pitch angle is 5º, and a steady state simulation of the fluid domain is carried out. The kw-SST turbulent model is used to capture wall shear effects around the blade wall. A Y^+ (dimensionless boundary layer parameter) value of one (1) (which is much lower than 5, the upper laminar flow limit) was used in determining the grid spacing at the boundary layer, and inflation layers (boundary layers) with ten steps was added around the blade surface; this help resolves the boundary layer accurately. The periodic boundary condition was used to mimic 3 rotating blades. Coupled algorithm and pseudo transient algorithm were used in the numerical set-up. The simulation was run in at a velocity of 6 m/s and a tip speed ratio (TSR) of 6. The software used for the simulation is ANSYS 20 which uses finite volume method (FVM) of analysis for solving governing flow equations.

2.1 Governing Flow Equations and Boundary conditions

To obtain the numerical solution of fluid domain particularly the velocity and pressure fields, equations of motion (Continuity, Navier-and Stokes) are discretized and solved by software. Secondary aerodynamic variables are then determined.

Continuity equation [14]:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho V) = 0 \quad (1)$$

Navier-Stokes's equation [14]:

$$\rho \frac{\partial V}{\partial t} + V.\nabla(\rho V) = \nabla.\tau_{ij} - \nabla P + \rho F \quad (2)$$

Where

$$\nabla = \left(\frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z}\right) \quad (3)$$

When the boundary conditions and the initial conditions are specified, the governing equations of fluid motion could be solved. Boundary conditions were specified in this work; the inlet and outlet fluid velocities were specified as the free air stream velocity (V_0). The pressure and velocity fields within the flow domain were obtained on solving the fluid flow equations by the software (ANSYS 20) and then calculated for drag and lift forces and hence the torque values. Using relationships, the coefficient of performances were then determined.

2.2 Equations for Blade Design and Results Analysis

The pressure and the velocity of a fluid changes when it is flowing past an airfoil which make it diverts from its original direction. The fluid experiences resistance force (or drag force) as it flows due to its viscosity. This force and the force due to the pressure over the surface of the body (the lift force) are collectively the resultant force exerted by the fluid on the body, known as the aerodynamic force. Figure 3 shows the direction of these forces exerted by the fluid on the airfoil.

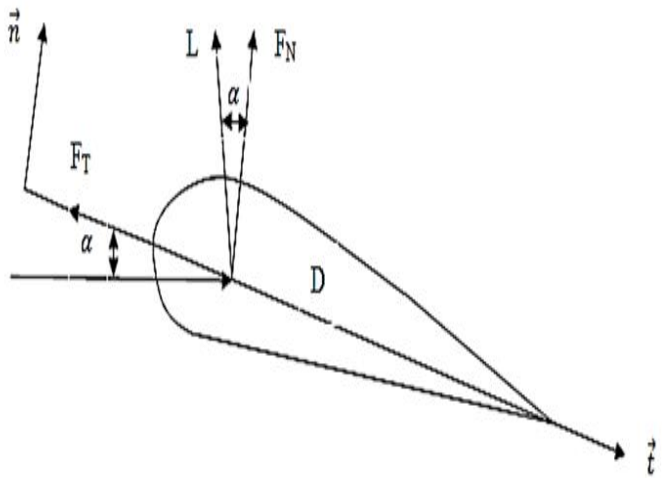

Figure 3: Airfoil Aerodynamic forces

Where D is drag force per unit length, L is lift force per unit length, F_N is total normal force per unit length, F_T is total tangential force per unit length, $\vec{t}$ is unit vector aligned to the chord, and $\vec{n}$ is unit vector perpendicular to the chord.

Equations 4 to 9 provide the relationships used for blade design and analysis of results:

Optimum chord length (C_{opt}) across the whole length of the blade [15]:

$$C_{opt} = \frac{2\pi r}{B}\frac{8}{9C_L}\frac{V}{\lambda V_r} \quad (4)$$

Where B is the blade count, λ is local tip speed ratio, V_r is local resultant air velocity (m/s), r is local radius, C_L is lift coefficient, and V is design wind speed.

Blade pitch angle (β) at a particular radial station (r) [15]:

$$\beta(r) = tan^{-1}\left(\frac{2R}{3r\lambda}\right) - \alpha \quad (5)$$

Where R is swept radius, λ is tip speed ratio, and α is the design lift coefficient.

Tip speed ratio (λ) and angular velocity (ω) [15]:

$$\lambda = \frac{V_t}{V} \quad (6)$$

$$\omega = \frac{V}{r} \quad (7)$$

Where V_t is the blade tip speed, V is the wind speed, and r is radius.

Power (P) and power coefficient (C_P) [15, 16]:

$$P = T\omega \quad (8)$$

$$C_p = \frac{P}{\frac{1}{2}\rho A V^3} \quad (9)$$

Where T is torque, ω is angular velocity, A is swept area, V is wind velocity, ρ is air density, and P is power.

2.3 Grid Independent Study and Validation of Results

The grid (mesh) resolution within the fluid domain in this work was varied from lower to higher resolution until no significant change of result obtained. The grid generated contains the necessary resolution to sufficiently simulate the flow physics as it is necessary for accurate solution of the problem to find a grid independent solution. The grid study was conducted at a wind velocity of 6m/s, a pitch angle (β) of 5^0 and tip speed ratio (λ) of six. The results of the study are shown in Table 1.

Table 1: Grid convergence study

Grid	Resolution (Cells)	Torque (Nm)
1	2273000	0.0355
2	3805500	0.0498
3	4526500	0.0550
4	4955700	0.0554

There is a significant change in torque value from the first grid to the third one, but after the third grid, its value changed by only 0.004 which is insignificant despite the large difference in the resolution (429200 cells). In order to save computation time and still maintain accuracy, the third grid with a resolution of 4526500 cells was chosen as the bases for all the grids in this work.

Betz limit (0.593) is the maximum theoretical value of wind turbine rotor performance coefficient (C_p), but however, the value of C_p of the Blade in this work is 0.2995 (calculated from the torque value (0.0550) of the third grid in Table 1) and is not up to the limit. According to Rao and Parulekar [17], C_p value reduces by factor of 0.5 to 0.7 in practice due to spillage, tip loses, etc. as to the reason why the value of the C_p in this work is less. Secondly, the blades were not twisted. This reason could helped reduced the C_p values. According to Fei et al. [18] analysis on the effect of blade twist and taper on blade performance of a model with twist (OPT) and another without twist (UUT), the C_p value of UUT is about 50% lower than that of OPT. Had the blade models of this research work were twisted their C_p values could be around that of OPT model (0.428). There are advantages to having a twist, the wind hits different parts of the moving blade from the root to the tip at different angles, but there have to be an optimum angle between the direction of the wind and the blade chord length for maximum lift, hence designing in some twist. The blade model used to compare its performance with that of blade created in this study is from the work of Kunya et al. [11], and has no twist, which is the reason why the blade model of this work was not twisted for proper comparison.

3.0 RESULTS AND ANALYSIS

In this study, simulations were run at 6m/s and a TSR of 6. The torque values obtained are for a single blade, and hence the power coefficient (C_P) values are determined by using equations 8 and 9. To account for 3 blades, the C_P values are then multiplied by 3; so the C_P values given in Table 2 (see Figure 4 for a plot) are based on 3-bladed turbine rotors. It has being a practice that to simulate for a 3-bladed rotor rotating through 360^0, one blade could be simulated and rotated through 120^0 and the result been multiplied by three (3) to obtain equivalent 3-bladed rotor computation result. Kunya et al. [11] used the same approach in their study as this method significantly reduces modelling and computation time.

Table 2: Power coefficient values for the two rotors

Rotor Type	Power Coefficient
D4-Rotor	0.2370
D4/5-Rotor	0.2995

Comparing the power coefficients for the two rotors (Table 2), the D4/5-Rotor has higher coefficient of performance (0.2995) than that of D4-Rotor (0.237), this shows that smaller wind turbines are more efficient than the bigger ones in terms of wind energy conversion at low wind speed tested. This is because the spillage loss of smaller wind turbine rotor could be smaller than that of relatively bigger wind turbine rotor. Another advantage of small wind turbine is that they could start at even lower wind speed, that is, it has lower cut-in wind speed.

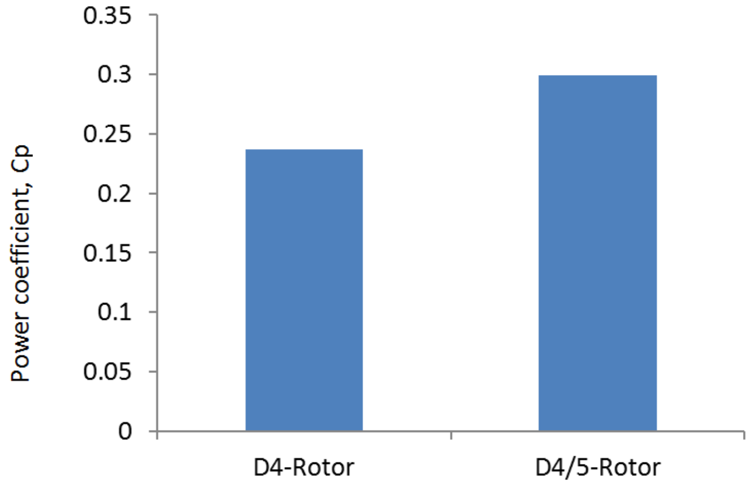

Figure 4: Power coefficient values for the two rotors

4.0 CONCLUSIONS

In this research work two different sizes of roof top wind turbine rotors were studied at low wind condition, a 4 metre rotor (D4-Rotor) and a 4/5 metre one (D4/5-Rotor). The effect of their sizes was analyzed. The D4/5-Rotor has higher coefficient of performance (0.2995) than that of D4-Rotor (0.237). Conclusively, smaller wind turbines are more efficient than the bigger ones in terms of wind energy conversion and they are therefore good for small power generation especially in low wind regime.

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