

# Development of a micro-vertical axis wind turbine to power traffic light in Maiduguri city

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## Abstract:

The utilization of wind to generate power provides an alternative and renewable energy source compared to current fossil fuel-based power generation. The world's fossil fuel energy is finite and is depleting at a faster rate. Moreover, fossil fuel is directly related to air pollution, and land and water degradation. Despite significant progresses being made in power generation using large-scale wind turbines recently, domestic-scale wind turbines especially vertical axis wind turbines have received less attention which has immense potential for standalone power generation. This work examines the advantages of a micro vertical axis wind turbine that can be used for power generation in built-up areas. It also describes the development and experimental studies performed to investigate the performance of a 1meter long Vertical Axis Wind Turbine blade on a 1.5meter stand using 8° as an angle of attack. The blade was design using the Blade Element Momentum Theory (BEM), blade parameters such as the chord length, angle of attack, Tip Speed Ratio, Rotor diameter, Lift and Drag force were determined. The designed blade profile was developed and tested on an open field at Maiduguri where the average wind speed is 3.89m/s, the results shows that the maximum extractable power is 15 W with a mean efficiency of 28% at a wind relative velocity of 4.2m/s when the blade is at 8° angle of attack.

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## 1. Introduction

Electricity is a form of energy generated by the movement of electrons through a conductor which is mostly related to the conversion of kinetic energy into mechanical energy. Electrical energy is essential to the activities of a man like operating household systems, office equipment, industrial processes, and transportation. Most generation of electricity presently depends on the use of natural resources such as fossil fuels that are limited and are accessed using methods that are damaging to man's ecosystem. Non-conventional energy is electricity produced from renewable sources such as wind power, solar power, geothermal energy, hydropower, and various forms of biomass. Because of their constant replenishment and availability for use over and over, these sources have been dubbed renewable. Due to the exhaustion of traditional power generation techniques, renewable energy has seen a significant increase in popularity in recent years. Renewable energy has been in increasing demand recently due to over-stress on non-renewable resources and their increasing cost [1]. Thus, producing electricity with the use of renewable resources, Wind energy has been taken up in this project.

Wind power Technology has played a significant role in power production. The wind turbine is used for converting the kinetic energy of wind into electrical energy. The wind

energy created by uneven heating of the Earth's surface by the sun is converted into useful energy for electricity generation by a turbine, Wind simply air in motion is an abundant resource available in nature that could be utilized by mechanically converting wind power using wind turbines for generation of electricity, grinding grain, pumping water in rural areas and draining of water from lowland areas [2].

Investigation carried out on the prospect of wind energy utilization reveal that an extractable power from wind in Maiduguri Borno State north eastern Nigeria gives a mean energy density of 42kWh/m<sup>2</sup> of electricity with the mean wind speed of about 3.89m/s and probability of occurrence between 75% to 80% in a year, these makes Maiduguri in Borno State to be one of the highest in prospect for wind generated electricity in Nigeria [3]. The aim of the work is to develop and carry out performance test of a Micro-Vertical Axis Wind Turbine. Based on this goal, the study is set to achieve the following objectives:

- Design the Micro-Vertical Axis Wind Turbine.
- Physically develop the Micro-Vertical Axis Wind Turbine.
- Experimentally verify the design criteria by testing the Micro-Vertical Axis wind Turbine.

The vertical axis wind turbine was chosen for this project to convert wind mechanical energy into electric energy for power generation.

The main reason behind developing Micro-Vertical Axis Wind turbines (MVAWT) is that they work regardless of the wind direction. MVAWTs do not require a yaw mechanism and are very fixed in the sense that no change to their direction or that of the blade is made once installed. The lack of a yaw mechanism is one of the reasons VAWTs are not as expensive or complicated to make. This makes them ideal for small-scale applications such as remote areas with very small electric loads. Their blades do not require a mechanism to change their angle as they work with any wind direction. VAWTs are considerably less noisy than Horizontal Axis Wind Turbines (HAWTs), which makes them more socially accepted. In addition to this, the small size means they can be integrated easily within an urban setting, and present no danger to the wildlife in rural areas. They still share many components with HAWTs such as the shaft, the gearbox, the tower, and the generator unit. The placement of these units is different since in VAWTs the gearbox and generator are placed at the base of the unit and do not require as much support as in HAWTs. This means easier access to maintenance and repairs, which lowers the overall cost of such systems [4].

## 2. Materials and Methods

### 2.1 Study Area

Maiduguri is a city found in Borno North-eastern Nigeria. It is located at 11.85 latitude and 13.16 longitudes and it is situated at elevation 325 meters above sea level. Maiduguri, also called Yerwa by locals, is the capital and the largest city of Borno State. The city sits along the seasonal Ngadda River which disappears into the Firki swamps in the areas around Lake Chad.

### 2.2 Materials

Materials used in the design and construction of this work are; Aluminum sheet, mild steel, plywood (Obeche), wood polish, paint, bearing, generator, and critical weather conditions of the study area.

The materials selected must possess the necessary properties for the proposed application, lightweight, rigidity, toughness, and good surface finish, ability to withstand environmental attack (weather and climate), service life, and reliability requirement to fulfill. The selection process of blade materials, supporting stand, shaft, pulley, and belt is followed based on physical properties, mechanical properties, and manufacturing processes.

### 2.3 Methods

The method adopted for this working designing the Micro-Vertical Axis Wind Turbine Blade is Blade Element Momentum (BEM) Theory; Blade Element Momentum (BEM) method is the oldest and remains to be the most widely used method for predicting wind turbine performance. It was originally developed by Glauert H. a German aeronautical engineer in 1935, which combined blade

element theory and momentum theory to analyze airplane propeller performance [5].

## 2.4 The wind turbine parameters

Turbine parameters considered in the design process are swept area, Blade airfoil, Angle of Attack, Blade chord, lift force ( $FL$ ) and drag force ( $FD$ ), Number of blades, Tip speed ratio, Solidity, Power Transmission, Power and power coefficient, and Tip speed ratio. Average wind velocity in Maiduguri 3.89 m/s. [6].

## 2.5 Design calculations

### 2.5.1 Swept area

The swept area is the section of air that encloses the turbine in its movement, the shape of the swept area depends on the rotor configuration, this way the swept area of a HAWT is circular shaped while for a straight-bladed vertical axis wind turbine, the swept area has a rectangular shape and is calculated using:

$$A = 2RL \quad (1)$$

Where A is the swept area [ $m^2$ ],

R is the rotor radius = [0.5 m], and

L is the blade length = [1 m].

$$A = 2(0.5) \times 1 \quad (2)$$

$$A = 1m^2 \quad (3)$$

The swept area limits the volume of air passing by the turbine. The rotor converts the energy contained in the wind in rotational movement so as the bigger the area the bigger the power output in the same wind conditions.

## 2.6 Blade Airfoil

The choice of an airfoil is important for the efficiency of the wind turbine, which takes into account factors including blade aerodynamic performance, blade quality, and manufacturing difficulty [7]. The baseline for the aerodynamic design of the VAWT blade is the National Advisory Committee for Aeronautics (NACA) 0018 airfoil data. Based on the airfoil data, modified blade geometry and orientation are aerodynamically designed. The aerodynamic design is carried out using the Blade Element Momentum theory.

## 2.7 Angle of Attack

The angle of attack is the angle between the incoming flow stream and the chord line of the airfoil as in Figure 2. It is a required input in Design Foil Workshop software to find the values of the lift coefficient ( $CL$ ) and coefficient of drag ( $CD$ ) of the airfoil at a predetermined Reynolds number ( $Re$ ). The coefficient of Lift to coefficient Drag ratio is calculated for angles of attack from  $0^\circ$  to  $12^\circ$  for wind speed from 0 to 10 m/s. Lift and drag coefficients are factors in determining the magnitude of lift ( $FL$ ) and drag ( $FD$ ) force acting on the airfoil section as shown in Figure 2, [6, 8]

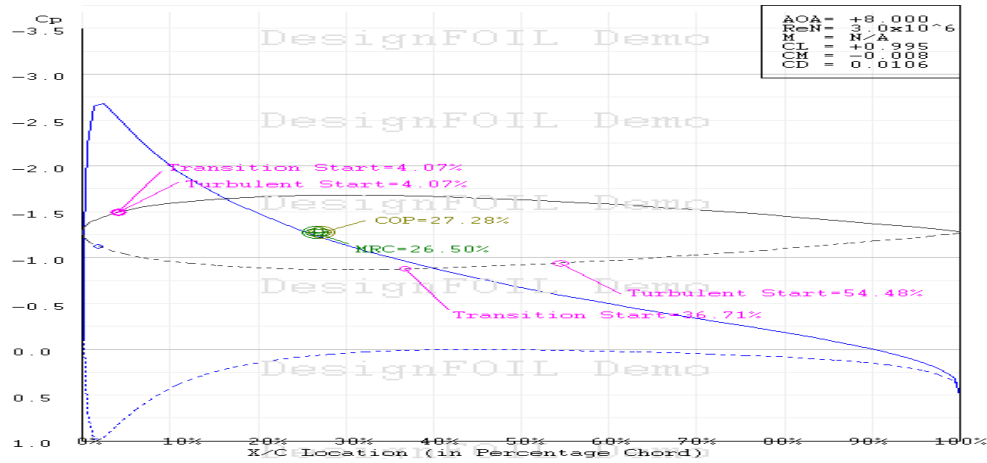


Figure 1: The Blade Airfoil

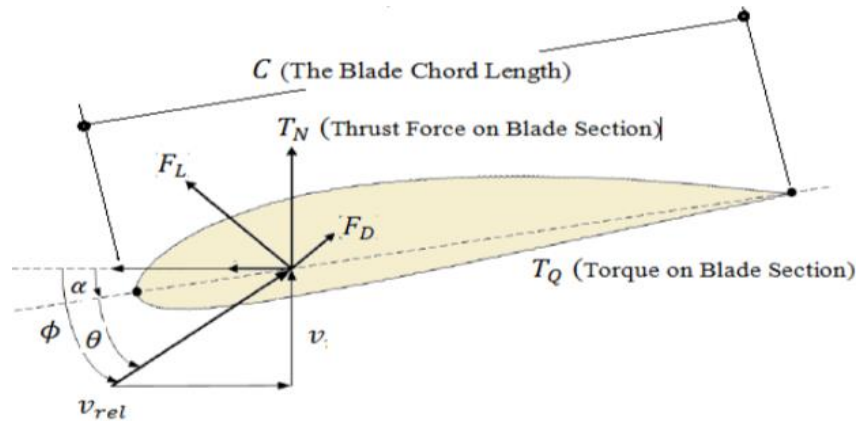


Figure 2 Airfoil Parameters

The lift force ( $F_L$ ) which is the force acting on the blade airfoil perpendicular to the undisturbed wind flow is determined from Equation 4. The drag force ( $F_D$ ) is the force acting on the blade airfoil in the direction of the undisturbed wind flow as given by Equation 5.

$$F_L = \frac{1}{2} \rho V^2 CL C_L \quad [4]$$

$$F_D = \frac{1}{2} \rho V^2 CL C_D \quad [5]$$

The lift and drag are available as functions of the angle of attack and the Reynolds number (Re). Also, the magnitude of lift and drag force is influenced by the blade's angle of attack and the Reynolds number (Re). Reynolds number (Re) as given by Equation 6 is the ratio of inertial forces to viscous forces within a fluid that is subjected to relative internal movement due to different fluid velocities.

$$Re = \frac{C v_{rel} \rho}{\mu} \quad [6]$$

## 2.8 Chord Length

The chord length ( $C$ ) of a blade airfoil is the length from the leading edge to the trailing edge of a blade cross-section that is parallel to the vertical axis of symmetry as shown in Figure 2 and it is obtained from Equation 7

$$C = \frac{8\pi r}{BC_L} (1 - \cos\phi) \quad [7]$$

## 2.9 Number of Blades

The number of blades has a direct effect on the smoothness of rotor operation as they can compensate for cycled aerodynamic loads. The choice of blade number is a critical design consideration and is ultimately a compromise between the blade stiffness, aerodynamic efficiency, and cost considerations. The number of blades has a direct effect on the smoothness of rotor operation as they can compensate for cycled aerodynamic loads. The number of blades has a significant effect on the torque whereby more blades create a less variable instantaneous shaft torque [6]. For this project, three blades have been contemplated.

## 2.10 Tip Speed Ratio

The power coefficient is strongly dependent on the tip speed ratio, defined as the ratio between the tangential speed at the blade tip and the actual wind speed [9].

$$TSR = \frac{\text{Tangential speed at the blade tip}}{\text{Actual wind speed}} = \frac{R\omega}{V_o} \quad (8)$$

Where,

$\omega$  is the angular speed [rad/s],  $R$  the rotor radius [m] and  $V_o$  the ambient wind speed [m/s].

$\omega = 15.2$  rad/s,  $R = 0.5$  m,  $V_o = 3.89$  m/s

$$\frac{0.5 \times 15.2}{3.89} = 2$$

Each rotor design has an optimal tip speed ratio at which the maximum power extraction is achieved. This optimal TSR presents a variation depending on ambient wind speed.

## 2.11 Solidity ratio

The solidity ( $\sigma$ ) is defined as the ratio between the total blade area and the projected turbine area. It is an important no-dimensional parameter that affects self-starting capabilities and for straight-bladed VAWTs is calculated with ( $\sigma$ ) [10].

$$\sigma = \frac{N C}{R} \quad [9]$$

Where,

N is the number of blades,

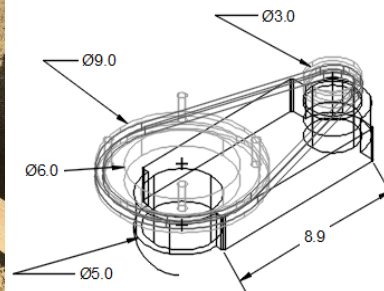
C is the blade chord,

R is the blade radius

$$\sigma = \frac{3 \times 0.282}{0.5} = 1.69$$



Figure 3. Dimensions of pulleys and belt designed for power transmission.



## 2.12 Power Transmission

A belt drive mechanism is selected for the transmission of power from the turbine to the generator. The pulleys are selected based on the generator rating and the speed of the turbine at average wind speed. [11].

Angular speed ( $\omega$ )

$$\omega = \frac{V}{R} \quad [10]$$

Where,

R the rotor radius [m] and

V the ambient wind speed [m/s]

$$\frac{3.89}{0.5} = 7.6 \text{ rad/sec}$$

Rotor revolutions per minute is given by

$$RPM = \frac{\omega}{2\pi} \times 60 \quad [11]$$

$$= \frac{7.6}{2\pi} \times 60 = 73 \text{ rpm}$$

The selected generator has a minimum rating of 350 rpm therefore the rotor generator pulley ratio is 3:1.

## 2.13 Power and power coefficient

### 2.13.1 Power Coefficient

Albert Betz [12] concluded that no wind turbine can convert more than 16/27 (59.3%) of the kinetic energy of the wind into mechanical energy turning a rotor. To this day this is known as the Betz limit. The theoretical maximum energy of any design of wind turbine is 0.59. This is known as the power coefficient [7]. Defined as

$$C_{P_{MAX}} = 0.95 \quad (12)$$

### 2.13.2 Power Calculations

The wind turbine works on the principle of converting the kinetic energy of the wind to Mechanical energy. The kinetic energy of any particle is equal to one-half its mass times the square of its velocity, [7].

$$KE = \frac{1}{2} MV^2 \quad (13)$$

Where,

K.E = kinetic energy

m = mass, v = velocity,

M is equal to its Volume multiplied by its density p

$$M = \rho AV \quad (14)$$

Substituting equation (14) in equation (13), we get,

$$KE = \frac{1}{2} \rho AV \cdot V \quad (15)$$

$$Power = \frac{1}{2} \rho \cdot A \cdot V^3 \cdot 0.59 \text{ watts} \quad (16)$$

Where,

A = swept area of the turbine.

$\rho$  = density of air (1.225 kg/m<sup>3</sup>)

V = wind velocity.

Average Power developed by the turbine

$$Power = \frac{1}{2} \times 1.225 \times 1 \times (3.89)^3 \times 0.59 = 21.27 \text{ watts.}$$

## 2.14 Fabrication of blades

The blade used for this prototype is highly simplified; it was made using a softwood and Aluminum (0.2mm) sheet. The softwood was first machined into the NACA 0018 geometry, using a blade length of 1m and chord length of 0.281m. Square cavities were formed in the softwood in order to create the blade frame. Aluminum was finally used to completely wrap the wooden frame making it air-tight. Holes for 12mm bolts and nuts were finally drilled at the center of the blade. This process was repeated for 2 other blades.



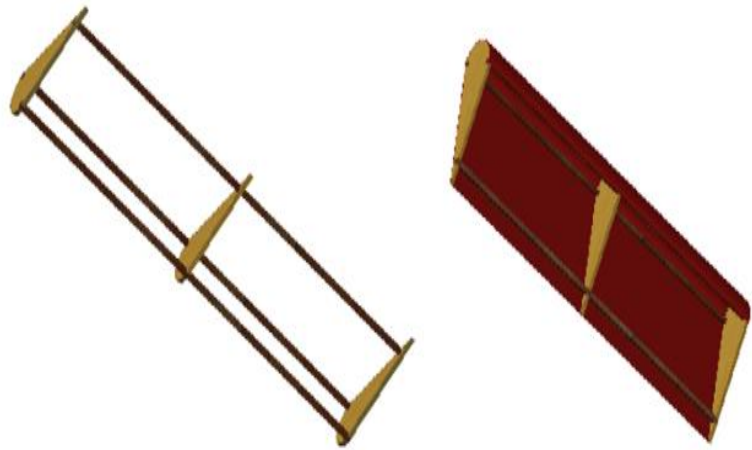


Figure 4. Modeled turbine blades

### 2.15 Rotor Configuration

Three Rotor configurations exist having attached blades by two points, the configuration adopted for the present work is that which correspond to the Bessel points and minimize the maximum bending moment. These points are located at 20.7% of the blade length from each blade tip; a procedure for obtaining these points by static analysis can be found at [13] which will reduce the resulting drag associated with the central mast and struts.

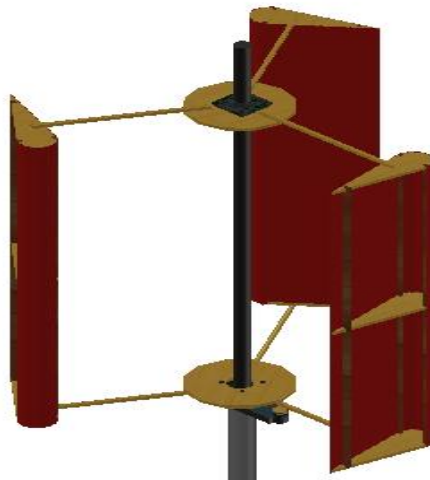


Figure 5: Modeled turbine rotor

Table1. The developed blade specifications as calculated

S/No	Parameter	Specification
1	Chord length (C)	0.282m
2	Blade span (L)	1m
3	Rotor diameter	0.5m
4	Swept area (A)	1m <sup>2</sup>
5	Angle of attack ( $\theta$ )	8°
6	Tip Speed Ratio	2
7	Coefficient of lift	0.995
8	Lift force	4.4N
9	Coefficient of drag	0.0106
10	Drag force	0.047N
11	Reynolds Number	3 x 10 <sup>6</sup>
12	Solidity Ratio	1.69

Note: Coefficient of lift and Coefficient of drag  
Obtained from Design Foil Workshop Software

Table.2 Rotor Parameters

S/No	Rotor parameter	Value
1.	Rotor diameter	1m
2.	Blade length	1m
3.	Blade Chord(constant)	0.281m
4.	Blade Airfoil	NACA 0018
5.	Number of blades	3
6.	Windspeed	3.89m/s
7.	The initial angle of attack	8°
8.	Tip speed Ratio	2
9.	Solidity	1.69



Plate1.The Micro-Vertical Axis Wind Turbine Physical Model on Test

## 3. Results and Discussions

### 3.1 Results

The results of this experimental work were obtained at the University of Maiduguri Centre for Entrepreneurship and Enterprises Development (CEED), where wind speeds and voltage output from the vertical axis wind turbine (VAWT) were measured. The turbine was observed to be self-

starting and also responding to wind speed blowing from any direction. Based on this behaviour of typical darrieus type vertical axis wind turbines, the data was observed in the space of three days as presented below:

Table 3. Data collection days

Days	Date	Time (hr)	Temp. (°c)	Top wind speed (m/s)
Day 1	Dec., 30, 2022	9 - 12pm	27.1	4.8
Day 2	Jan., 4, 2023	12 - 4pm	31.3	4.0
Day 3	Jan., 5, 2023	4 - 6pm	27.9	4.5

Table 4. Data collected from the turbine at different wind speed intervals on day 1.

S/N	Wind speed (m/s)	Voltage (volts)	Current (ampere)	Power (watts)	Efficiency (%)
1	0.90	1.10	0.61	0.67	3.53
2	1.10	1.35	0.75	1.01	5.32
3	1.90	2.00	1.11	2.22	11.68
4	2.30	2.20	1.22	2.68	14.68
5	2.80	2.55	1.42	3.62	19.05
6	3.40	3.00	1.67	5.01	26.34
7	3.80	3.25	1.82	5.92	31.16
8	4.00	4.90	2.72	13.33	70.16
9	4.20	5.14	2.86	14.67	77.21
10	4.80	5.40	3.00	16.20	85.26
Mean efficiency =					30.75 %

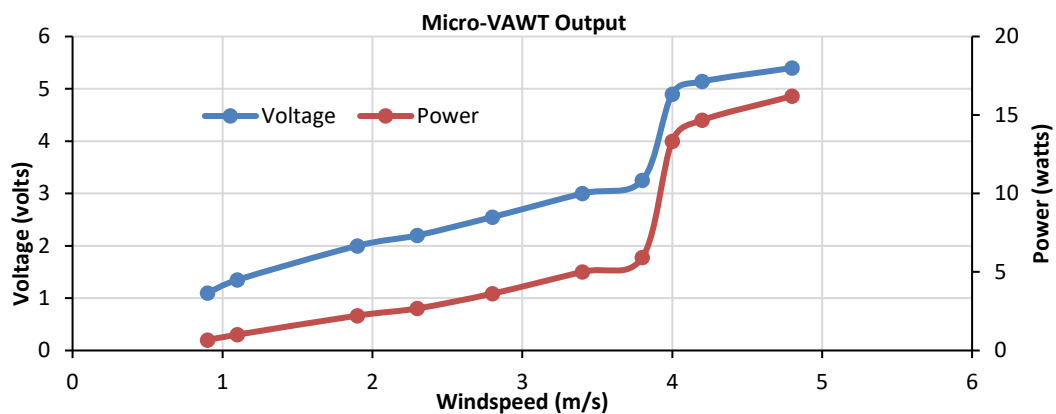


Figure 6. A graph of voltage (volts) and power (watts) against wind speed (day 1)

Table 5 data collected from the turbine at different winds peed intervals on day 2.

S/N	Wind speed (m/s)	Voltage (volts)	Current (ampere)	Power (watts)	Efficiency (%)
1	0.50	0.44	0.24	0.11	0.52
2	0.70	0.53	0.30	0.16	0.75
3	0.90	1.05	0.58	0.61	2.87
4	1.70	1.89	1.05	1.98	9.31
5	1.90	2.12	1.18	2.51	11.80
6	2.30	2.51	1.39	3.49	16.40
7	2.80	2.92	1.62	4.73	22.24
8	3.50	3.61	2.01	7.26	34.13
9	3.80	3.93	2.18	8.57	40.29
10	4.00	5.00	2.78	13.89	65.30
Mean efficiency =					22.28%

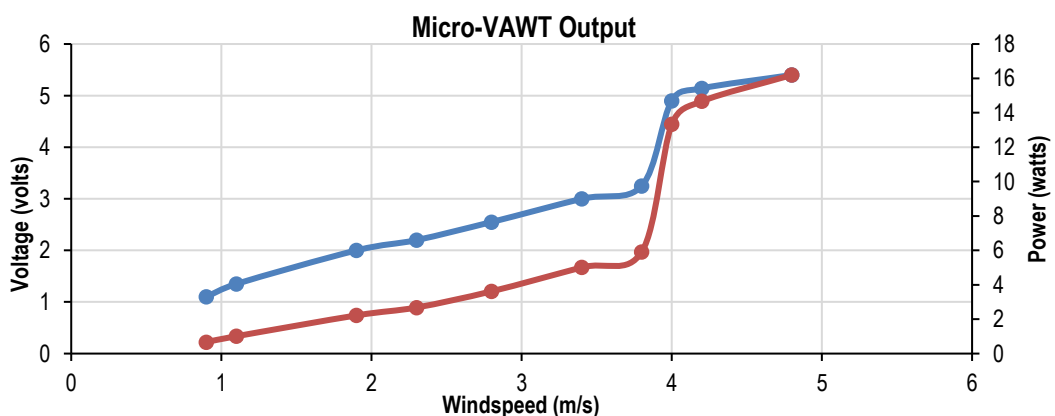


Figure 7: A graph of voltage (volts) and power (watts) against wind speed (day2)

Table 6 data collected from the turbine at different windspeed intervals on day 3.

S/N	Wind speed (m/s)	Voltage (volts)	Current (ampere)	Power (watts)	Efficiency (%)
1	1.10	1.34	0.74	1.01	4.74
2	1.50	1.78	0.99	1.76	8.27
3	1.90	1.85	1.03	1.91	8.98
4	2.30	2.11	1.17	2.50	11.75
5	2.80	2.68	1.49	4.00	16.46
6	3.20	3.39	1.88	6.37	29.95
7	3.60	3.84	2.13	8.18	38.46
8	3.90	4.01	2.23	8.94	42.03
9	4.00	4.98	2.77	13.79	64.83
10	4.50	5.21	2.89	15.08	70.89
Mean efficiency =					29.44%

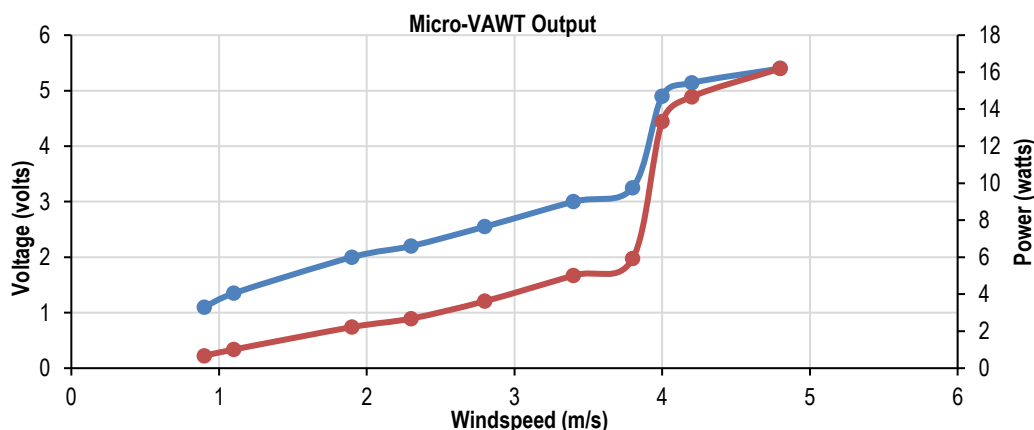


Figure 8 A graph of voltage (volts) and power (watts) against wind speed (day3)

### 3.2 Discussions

From the graph plotted and the calculations made using the values given in Tables 4, 5, and 6. Figs. 6, 7 and 8 showed that the relationship between wind speed and voltage developed by the generator is directly proportional. The graphs also indicated that the highest voltage the system could generate at the highest recorded wind speed was 5.2 volts (mean voltage for three days). This shows that the voltage the generator can develop is dependent on the wind speed. Likewise, the graphs show that the relationship between the wind speed and the power developed by the system is directly proportional. The graphs also indicated the maximum power the system could attain. Furthermore, the graphs indicate the highest power output of the generator throughout the testing period was approximately 15W, which corresponds to the highest point on the graphs.

The results obtained so far were very encouraging and re-enforce the conviction that vertical axis wind energy conversion systems are practical and potentially very contributive to the production of clean renewable electricity from the wind under an ideal condition, this work will be helpful in rural areas where the electricity supply is scarce especially with the current cost review of conventional energy resources. Also in most cities, bridges are a faster route for everyday commuters and in need of constant lighting making this an efficient way to produce energy.

#### 3.2.1 Total Power Generated

From the results collected from testing the three-bladed micro vertical axis wind turbine it can be seen that

the highest power output of the wind turbine and generator is 15W with a mean efficiency of 28% this work has an improved efficiency compared to the work carried out by Piyush, et al., [14] which had an efficiency of 23%. The electric power generated is sufficient to power a traffic light, charge a mobile device and power a low energy diode (LED) light bulb for domestic lighting.

### 4. Conclusion

A micro-vertical axis wind turbine has been developed, designed, constructed, and tested at Maiduguri with an air density of 1.225kg/m. The data showed that the mean efficiency was 28%. Therefore, it can be concluded that, by optimizing the selection of materials and fabrication method, a three-bladed micro vertical axis wind turbine can be very useful for low-speed power applications, The developed MVAWT has shown the ability to perform well and could be a means of extracting and generating energy from wind; a renewable, clean and locally available source of energy in Maiduguri. The conclusion can be summarized as follows:

- The system was developed with AutoCAD (2016 Version) for the design modeling.
- The system was tested and the mean power output was found to be 15W with an efficiency of 28%.
- No additional control mechanisms are required because it is independent of wind direction.
- Ability to operate in a wide range of wind conditions such as high and low wind speeds and direction.

- e. Low noise emission, compact size, simple and cheap in construction.

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