

## DESIGN, CONSTRUCTION AND TESTING OF A 3 METRE WIND TURBINE WITH NACA 4412 BLADE SECTION PROFILE IN LOW WIND SPEED AREA

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### ABSTRACT

*This paper reports the design, manufacturing and testing of a 3 metre three-bladed wind turbine rotor with NACA 4412 blade section profile. It also reports the test and analysis of the results. The blade tip speed ratio of 6 and angle of attack of 5° were used in designing the rotor (blade). The rotor was tested on the roof of mechanical engineering department, Ahmadu Bello university, Zaria at the hub height of 22 metres and achieved an efficiency (or performance) of 0.222 on the basis of projected 6.15m/s average wind speed from the ground level measurements.*

### 1. Introduction

The importance of electric energy in industry, agriculture, material processing, and communications cannot be over emphasized. The most common source of energy is the chemical energy of substances called fuels which is released in the form of heat upon the combustion of the fuel in air. This can either be used directly or be converted to electricity. However, the combustion of fuels leads to the production of gases such as carbon dioxide which causes a worsening of the greenhouse effect, global warming, and a general risk to the ecosystem from the other gaseous products (known as pollutants). Also, the earth's supply of fossil fuel may be finite. These are the reasons why alternative sources of energy are required for the future.

Wind power is certainly one of the most attractive solutions in the continuous search for clean, safe and renewable energy sources. Operating cost of wind energy conversion systems is small compared to their fossil fuel counterparts. However the serious problem with it is its unreliability. There are wide

variations in the speed and direction of winds. Also it does not possess the basic requirements of any energy resources i.e. ready availability and long lasting supply. To overcome this, wind energy can be stored in some other forms during periods of high winds so that it can be used later on and during calms.

### 2. Design Factors for a Wind Turbine

To design a wind turbine the wind speed at the point of installation of the wind turbine must be known, and if the height at which wind speed measurement was carried out is different from the height of location of the turbine, the wind speed must be extrapolated. The design and production of the rotor blade to meet NACA 4412 are presented. The theoretical wind power was determined, the actual wind power was measured when the turbine was installed and tested.

#### 2.1 Wind Speed Measurements

The wind speed of where to install or test a wind turbine system need to be known, and the wind speed of the area of testing was collected from the nearby meteorological station in Zaria.

### 2.2 Wind speed Variation with height

Apart from the seasonal and intermittent variations of wind speed at a particular location, it also varies with height. The wind blows faster at higher heights because of absence of the drag of the surface (sea or land) and the low viscosity of the air. The variation with height, called wind shear, is most dramatic near the surface. This variation can be extrapolated with reference to the actual height of measurement using the power law equation: (Rao and Parulekar, 1999).

$$\frac{v_2}{v_1} = \left( \frac{H_2}{H_1} \right)^n \quad (1)$$

Where,  $v_1$  and  $v_2$  are the wind velocities at the reference heights  $H_1$  and  $H_2$  respectively. Where  $n$  is an exponent whose value may depend on the speed at the reference height (Reed, 1974), the atmospheric stability (Smith, 1968), or on the surface roughness and atmospheric stability (Munn, 1966). According to Fales (1967), over an obstructed plain,  $n = 1/2$  for wind under 2.24m/s,  $n = 1/5$  from 5 to 15.65m/s, and  $n = 1/7$  above 15.65m/s. over irregular terrain having obstructions, only those velocities recorded at the site are valid for energy prediction. Peterson and Hennessey (1978) analyzed data from four tower sites and concluded that the use of the  $1/7^{\text{th}}$  power law should yield usually conservative yet reasonable wind speed and power estimates in situations where the roughness length for the site is at least an order of magnitude smaller than the height of the reference level (Pam, 2008).

Equation (1) was used in extrapolating the wind speed from the height where the wind measurements was carried out to the height where the turbine rotor was tested.

### 2.3 Available Wind Power

The wind power available (kinetic energy/unit time) for a wind turbine rotor is given by the expression (Shepard et al, 1976) as:

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

Where  $v$  and  $\rho$  are respectively the velocity and density of an air stream passing through a swept area of the turbine rotor  $A$  normal to the flow. The density of air  $\rho$  is 1.226 kg/m<sup>3</sup> at 1 atmospheric pressure and temperature of 15°C; from the ideal gas equation of state.

The available wind power for the rotor was calculated by using equation (2); been an input when determining its performance.

### 2.4 Actual Extractable Wind Power

It is not possible to convert all the wind energy into another form of energy because the load would reduce the wind speed through the turbine rotor to zero, thus stopping the machine. It is concluded from theoretical considerations that the maximum conversion rate for horizontal axis windmill known as Betz limit is 16/27 (0.593) of the available wind energy (Rai, 1994). Therefore, the wind power based on this efficiency is obtained by multiplying available wind power (equation-2) with the theoretical power coefficient (0.593) and given as:

$$P_{\text{max}} = 0.297 \rho A v^3 \quad (3)$$

In practice, the performance characteristics of the wind turbine also determine the total amount of extractable wind power. Rao and Parulekar (1999) show that, overall efficiency,  $\eta_{ov}$  is even less than the power coefficient,  $C_p$  by factor 0.5 to 0.7 due to mechanical friction, spillage, generation efficiency, etc. Actual extractable wind power is thus given by Rao and Parulekar(1999) as:

$$P_e = 1/2 \rho A v^3 \eta_{ov} \quad (4)$$

Above equations were used as an input to the turbine rotor for its performance determination.

### 2.5 Energy Pattern Factor

Wind energy pattern factor is the ratio of actual energy in varying wind to calculated energy from mean. It is always above one (1) (Rao and Parulekar, 1999).

$$EPF = \frac{\overline{v^3}}{v^3} \quad (5)$$

### 2.6 Design Methods of the Rotor Blades

There are great lengths that designers can go to for designing an aerofoil. But all an aerofoil needs is to maximize lift and minimize drag. The need is to optimize the lift force to satisfy the Betz criterion, but the blade will not work well unless the drag is minimized. So it is required to choose a section and an angle of attack, where the lift/drag ratio is high. The lift and drag forces are given by Zucrow(1976) as:

$$Lift = 1/2 C_L \rho A v_a^2 \tag{6}$$

$$Drag = 1/2 C_D \rho A v_a^2 \tag{7}$$

Where,  
 $C_L$  is lift coefficient,

$C_D$  is drag coefficient,  
 $\rho$  is air density, and  
 $v_a$  is apparent wind speed.

Lift and drag forces depend on the coefficients of lift,  $C_L$  and drag  $C_D$  which in turn depends on the cross section of the blade, and on the angle  $\alpha$  at which the wind strikes the blade. Lift and drag coefficients cannot be calculated. They are measured experimentally in wind tunnels, and recorded in books. The angle of attack  $\alpha$  is the angle the apparent wind direction makes with the chord line. When designing a wind turbine rotor, the angle  $\alpha$  will depend on the angle of the apparent wind  $\phi_a$ , and the blade angle  $\beta$ . As  $\alpha$  increases so does the lift, until a point is reached where the blade stalls.

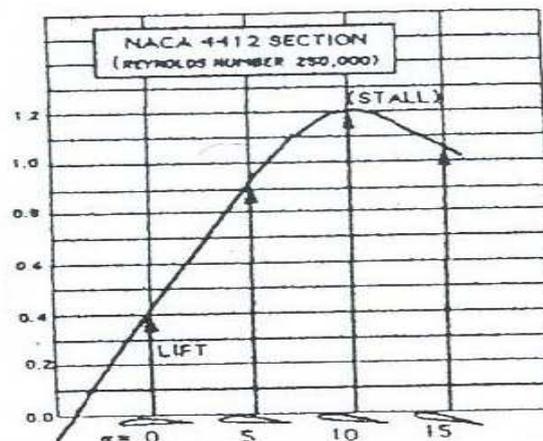
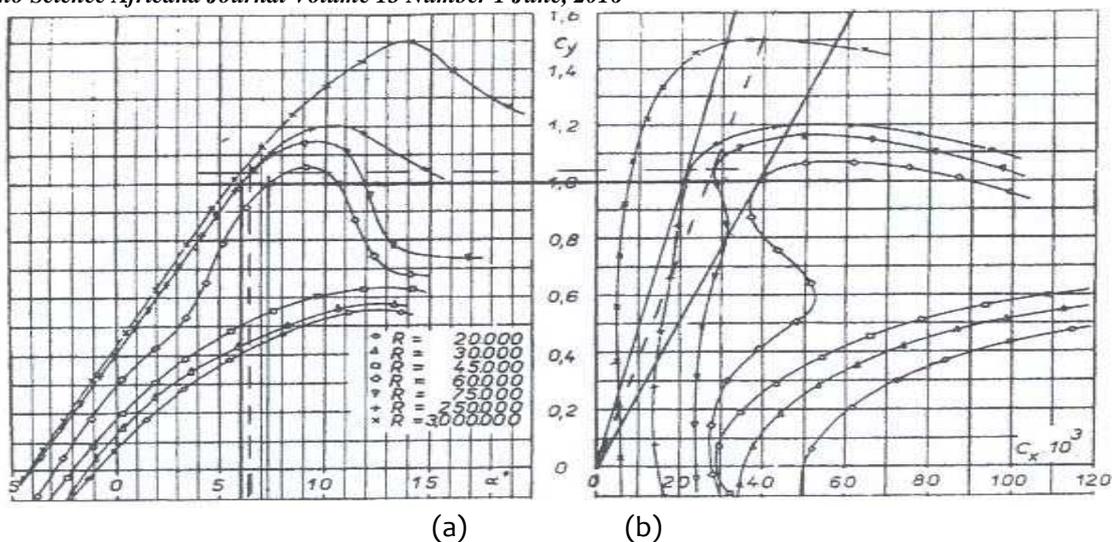


Figure 2.1 Lift coefficient versus angle of attack  
 (Source: [www.otherpower.com](http://www.otherpower.com))

Finding the best angle of attack  $\alpha$  can be an involved process, because the lift and drag coefficients depend on both the section and the Reynolds number (a measure of the size and speed of the blade). The figure 2.2 below is a pair of graphs which again relate to the NACA 4412 section for several different Reynolds numbers. The graph in (a) shows lift/ $\alpha$ , while that in (b) shows lift/drag. The

straight lines through zero represent particular lift/drag ratios. Best lift/drag ratio for a given Reynolds number occurs where the lift/drag line is rotated as far as possible anticlockwise, so that it just touches the curves as a tangent. For NACA 4412, this point of contact is where  $C_L$  is 1 and  $\alpha$  is about 6. ([www.otherpower.com](http://www.otherpower.com)).



**Figure 2.2** Graphs of Lift/ $\alpha$  and Lift/drag relationships for several Reynolds numbers  
(Source: [www.otherpower.com](http://www.otherpower.com))

To specify blade angle  $\beta$  it requires knowing the angle  $\phi_a$  at which the apparent wind strikes the rotor plane. Blade angle  $\beta$  is given as ([www.otherpower.com](http://www.otherpower.com)):

$$\beta = \phi_a - \alpha \tag{8}$$

Where  $\alpha$  is usually around  $5^\circ$  for NACA 4412 airfoil section.

$$\phi_a = \tan^{-1} \left\{ \frac{2R}{3r\lambda} \right\} \tag{9}$$

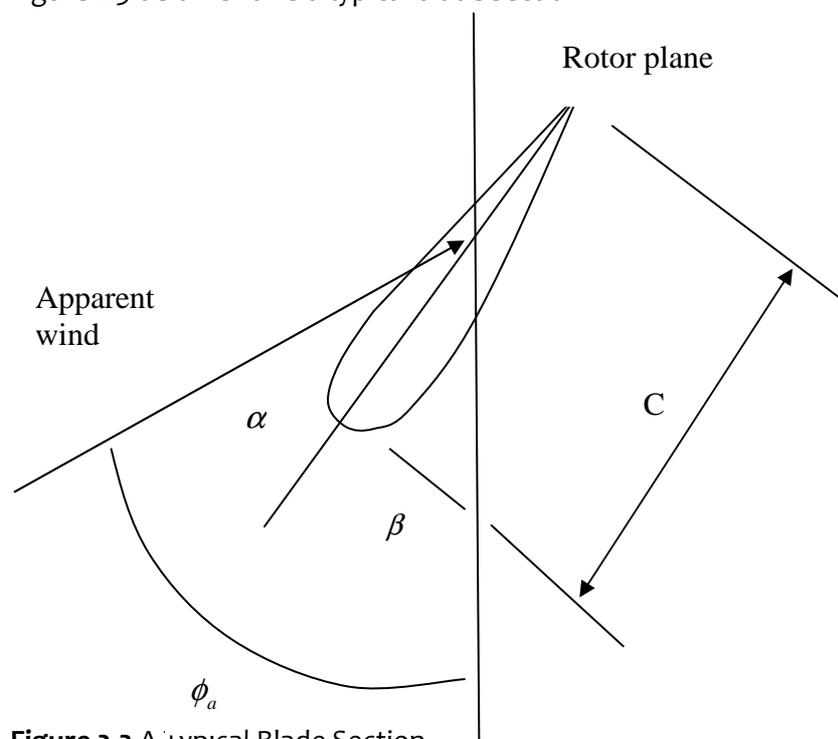
Where,

$\lambda$  is tip speed ratio

$R$  is the rotor radius

$r$  is the reference rotor radius

Figure 2.3 below shows a typical blade section.



**Figure 2.3** A typical Blade Section

Having worked out  $\beta$ , there is still need to work out the chord width, C.

To satisfy Betz limit, the wind in each part of the swept area of the rotor must be slowed down to 1/3 of its upstream velocity, and this slowing is done by the thrust force, which is very closely related to the LIFT force. The blade chord width (C) which will produce the right amount of the thrust to meet the Betz condition is given by the following relation ([www.otherpower.com](http://www.otherpower.com)):

$$C = \frac{16\pi R(R/r)}{9\lambda^2 B} \tag{10}$$

Where,

- R is radius of the rotor (m),
- r is reference rotor radius (m),
- B is number of blades, and
- $\lambda$  is tip speed ratio.

The rotor tested is three bladed ( $B=3$ ) with the radius of 1.75m. Choosing the tip speed ratio ( $\lambda$ ) as 6 for horizontal axis wind turbine for power generation, the blade chords/widths at four stations along the span of the rotor blades where determined by using equation (10) above and presented as in table (2.1).

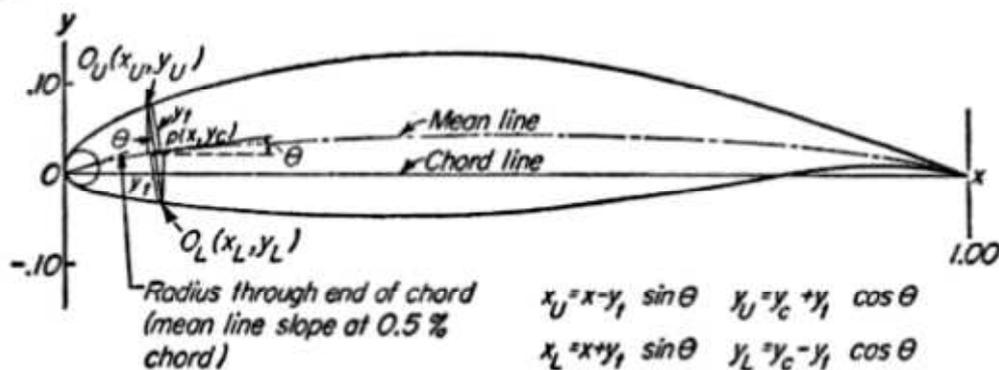
**Table 2.1** Blades Chords at Four Radial Stations

S/N	Stations (m)	Blade chord/width (m)
1	r = R = 1.75	0.0905
2	r = 1.25	0.1267
3	r = 0.75	0.2112
4	r = 0.25	0.6335

The blade sections profile for each of the above blade stations (or chord) were then determined based on the adopted airfoil section. The NACA 4412 airfoil section profile was adopted for the design of the blades geometry; the side facing the wind is flat, which makes the profile easy to construct. It is an effective profile with a good thickness, which makes the blade strong. It also has good stall characteristics, which makes the blade useful for low wind speed areas.

NACA 4412 is one of the families of NACA airfoils series known as the NACA-Four-Digits series which were generated using analytical equations that describe the chamber (Curvature) of the mean-line (geometry

centerline) of the airfoil section as well as the section thickness distribution along the length of the airfoil. The first digit specifies the maximum camber (m) in percentage of the chord (airfoil length), the second indicates the position of the maximum camber (p) in tenths of chord, and the last two numbers provide the maximum thickness (t) of the airfoil in percentage of chord. That is, the NACA 4412 airfoil has a maximum thickness of 12% with a camber of 4% located 40% back from the airfoil leading edge (or 0.4C). Utilizing these m, p, and t values, we can compute the coordinates of an entire airfoil using the following procedure:



**Figure 2.4** Illustration of the NACA airfoil geometry

1. Pick values of x from 0 to the maximum chord c.
2. Compute the mean camber line coordinates by plugging the values of m and p into the following equations for each of the x coordinates.

$$y_c = \frac{m}{p^2}(2px - x) \quad \text{from } x = 0 \text{ to } x = p \quad (11)$$

$$y_c = \frac{m}{(1-p)^2}[(1 - 2p) + 2px - x^2] \quad \text{from } x = p \text{ to } x = c \quad (12)$$

Where

x = coordinates along the length of the airfoil, from 0 to c (chord, or length)

y = coordinates above and below the line extending along the length of the airfoil, these are either  $y_t$  for thickness coordinates or  $y_c$  for camber coordinates

t = maximum airfoil thickness in tenths of chord (i.e. a 12% thick airfoil would be 0.12) m = maximum camber in tenths of the chord

p = position of the maximum camber along the chord in tenths of chord

3. Calculate the thickness distribution above (+) and below (-) the mean line by plugging the value of t into the following equation for each of the x coordinates.

4. Determine the final coordinates for the airfoil upper surface ( $x_U, y_U$ ) and lower surface ( $x_L, y_L$ ) using the following relationships:

$$x_U = x - y_t \sin\theta \quad (13)$$

$$y_U = y_c + y_t \cos\theta \quad (14)$$

$$x_L = x - y_t \sin\theta \quad (15)$$

$$y_L = y_c - y_t \cos\theta \quad (16)$$

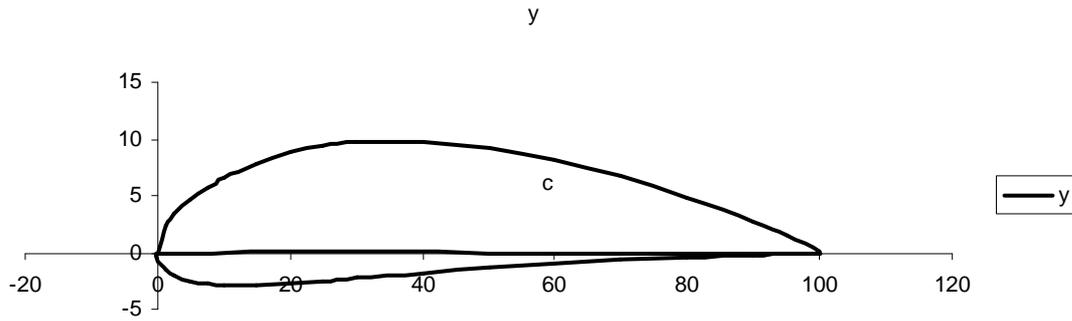
where  $\theta = \arctan\left(\frac{dy_c}{dx}\right)$

Based on the above procedure the blade section profile was determined and is as presented in table 2.2.

**Table 2.2** Coordinates of the NACA 4412 Airfoil Section in Percentage of Airfoil Chord

Upper surface		Lower surface	
x - axis	y - axis	x - axis	y - axis
0	0	0	0
1.25	2.44	1.25	-1.43
2.5	3.39	2.5	-1.95
5	4.73	5	-2.49
7.5	5.76	7.5	-2.74
10	6.59	10	-2.86
15	7.89	15	-2.88
20	8.80	20	-2.74
25	9.41	25	-2.50
30	9.76	30	-2.26
40	9.80	40	-1.80
50	9.19	50	-1.40
60	8.14	60	-1.00
70	6.69	70	-0.65
80	4.89	80	-0.39
90	2.71	90	-0.22
95	1.47	95	-0.16
100	0.13	100	-0.13
100	0	100	0

Figure 2.5 below represent a blade section profile based on the data presented in table 2.2 above.



**Figure 2.5** The Designed Blade Section Profile in Percentage of Airfoil Chord Length

### 2.7 Carving and Assembling the Rotor Blades

The rotor blades are made from wood (Afara). The rotor is three bladed, three blades were therefore constructed. The designed blade span profile was marked out on the surface of plank of wood of 50mm thickness. It was then cut out with hacksaw. The blade section profile was then shaped by marking out and material removal of the wood by chipping. Holes were drilled at the blade roots for assembling the blades to the rotor hub that is mounted on the rotor shaft. The blades were surface finished by polishing, and then painted

with emulsion paint. The blades were then assembled together to the nacelle (rotor shaft) placed on a tower that is on the roof of mechanical engineering department, Ahmadu Bello University, Zaria. The nacelle (with tail vane attached to it) encloses a transmission system which can generate electricity as the rotor (blades) rotate. The amount of electricity generated which depends on the wind speed was used in predicting the rotor performance. Relative to the design expectation, plate 1 shows the designed, manufactured, and assembled wind turbine.

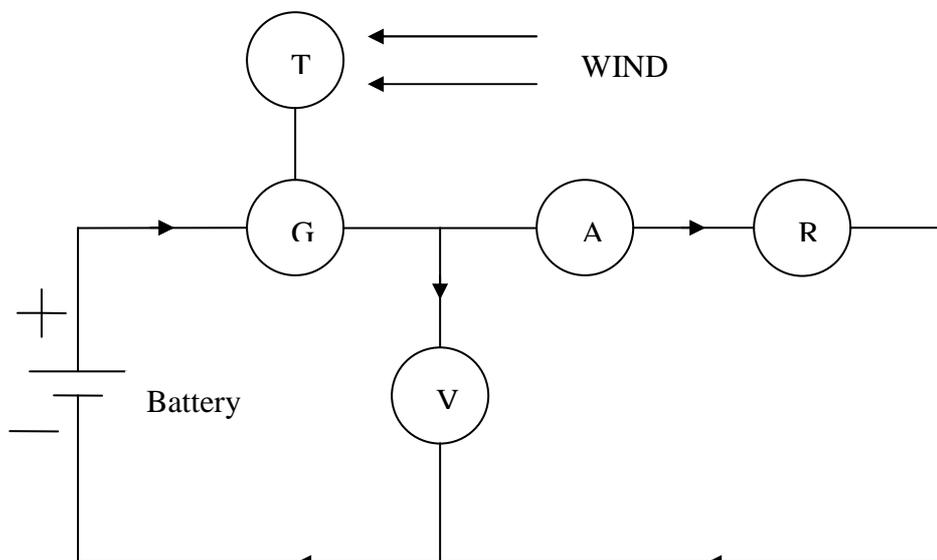


**Plate 1:**The Complete Assembly of the Wind Turbine Constructed

**3. Testing**

The line diagram of the test rig is shown in figure 3.1. The set-up comprised of a 0-45A range ammeter (A), 0-40V range voltmeter

(V), 12V/60AH storage battery, 300W electric load (R), and 75A/12V variable speed D.C. generator (G).



**Figure 3.1** Electric Power Measuring Set-up

The 3 metre wind turbine rotor was tested on the departmental building of Mechanical Engineering, Ahmadu Bello University Zaria at 22 metres height. The measurement was carried out between 1.00pm to 3.00pm local time on Saturday, 20<sup>th</sup> February, 2010. The rotor had the source of input from the wind power which was being intercepted. The rotor rotated the 75A/12V D.C. generator via transmission assembly and produced electricity. This made the ammeter to read the current (in Ampere) in the circuit and the voltmeter to read the voltage (in Volt) across the circuit. The output power in Watt (electric current in Ampere multiplied by the voltage in

Volt) of the system was measured and recorded every two minutes for two hours.

**4. Result and Discussion**

The output power in Watt of the system was measured and recorded every two minutes for two hours and the results are shown in table 4.1. The corresponding average wind speeds for the first and second hours of measurement as collected from the nearest metrological station (NCAT, Zaria) at 10 meters height are 6  $ms^{-1}$  and 5  $ms^{-1}$  respectively. Using exponential equation (1), with the extrapolation index,  $n=1/7$ . The average wind speeds at 22 m height of testing are thus, 6.7  $ms^{-1}$  and 5.6  $ms^{-1}$  respectively.

**Table 4.1:** The Wind Generator Power Output

S/N	Time (minute)	1 <sup>st</sup> Hour Power (Watt)	2 <sup>nd</sup> Hour Power (Watt)
1	2	158.7	94.0
2	4	185.0	105.5
3	6	192.3	165.5
4	8	188.7	211.0
5	10	177.6	210.0
6	12	210.8	131.5
7	14	225.6	55.5
8	16	240.4	30.0
9	18	229.3	118.5
10	20	203.4	20.0
11	22	203.4	211.5
12	24	221.9	150.4

13	26	236.7	215.0
14	28	240.4	166.0
15	30	236.7	113.0
16	32	233.0	50.4
17	34	188.7	86.5
18	36	159.1	130.5
19	38	74.0	215.0
20	40	81.4	100.5
21	42	74.0	108.3
22	44	66.6	114.6
23	46	140.6	37.3
24	48	133.2	0.0
25	50	133.2	61.7
26	52	166.5	146.0
27	54	203.4	122.6
28	56	255.2	105.3
29	58	258.9	89.5
30	60	251.5	46.0

It can be seen that the power output fluctuated. This is due to the variability of the wind velocity with time. The fluctuation pattern is as shown in figure 4.1.

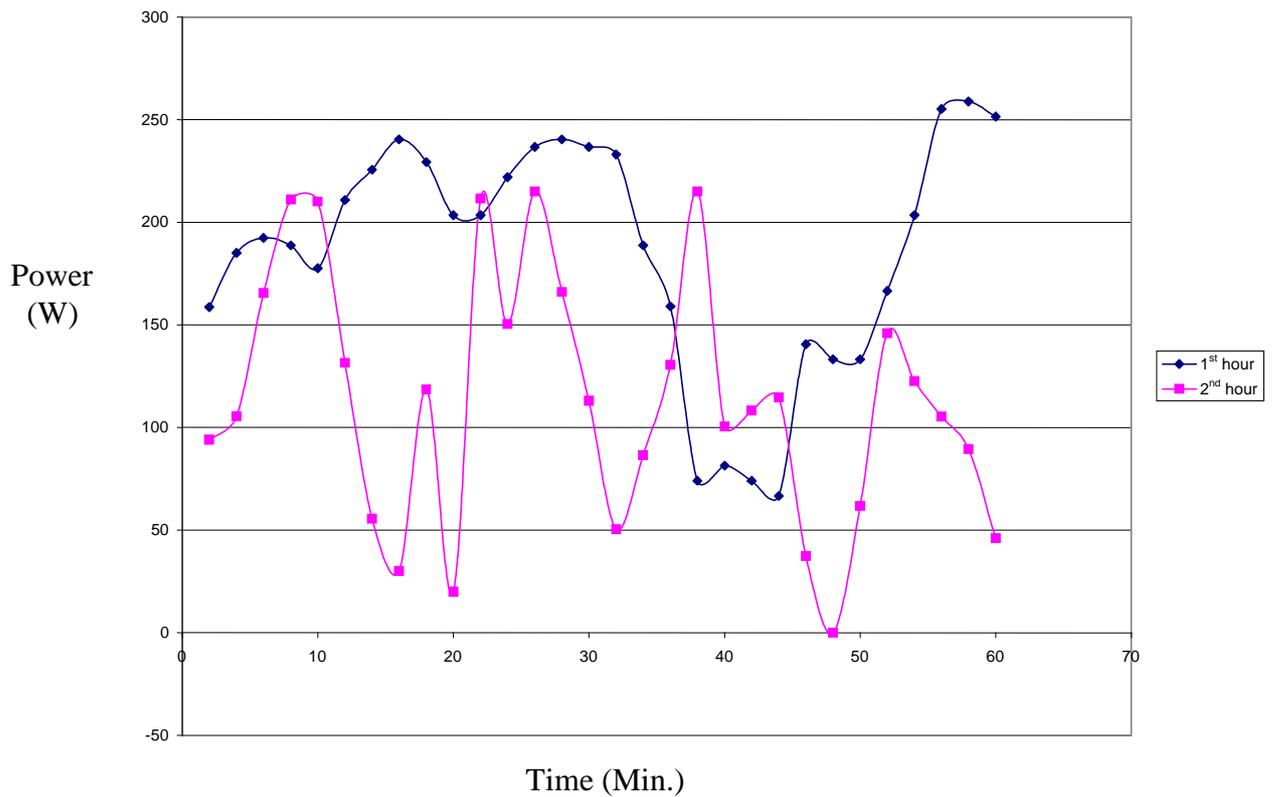


Figure 4.1 Instantaneous Power Outputs

The average power for the first hour,

$$\bar{P}_1 = 185.7 \text{ Watt}$$

The average power for the second hour,

$$\bar{P}_2 = 113.5 \text{ Watt}$$

From equation (2) the power from the wind,

$$P = \frac{1}{2} \rho A v^3$$

From the knowledge of energy pattern factor ( $EPF$ ) given by equation (6),

$$\bar{P} = \frac{1}{2} \rho A v^{-3} EPF$$

The energy pattern factor for Zaria for the month of February is 1.31 (Pam and Bala, 2006).  
For the first hour,  $v = 6.7 \text{ ms}^{-1}$ ,

$$P_1 = \frac{1}{2} \times 1.226 \times \frac{\pi \times 3^2}{4} \times 6.7^3 \times 1.31 = 1707.9 \text{ Watt}$$

Hence, the first hour efficiency,

$$\eta_{ov1} = \frac{\bar{P}_1}{P_1} = \frac{185.7}{1707.9} = 0.1087$$

For the second hour ( $V = 5.6 \text{ m/s}$ ),

$$P_1 = \frac{1}{2} \times 1.226 \times \frac{\pi \times 3^2}{4} \times 5.6^3 \times 1.31 = 997.2 \text{ Watt}$$

Hence, the second hour efficiency,

$$\eta_{ov2} = \frac{\bar{P}_2}{P_2} = \frac{113.5}{997.2} = 0.1138$$

Average overall efficiency,

$$\bar{\eta}_{ov} = \frac{\eta_{ov1} + \eta_{ov2}}{2} = \frac{0.1087 + 0.1138}{2} = 0.111$$

However, power losses in the transmissions and generators of wind turbines reduce the input power (aerodynamic power) so that measured power (output) need correction for studies of aerodynamic performance. Rao and

Parulekar (1999) showed that, the overall efficiency  $\bar{\eta}_{ov}$  is less than the aerodynamic power coefficient  $C_p$  by factor 0.5 to 0.7 due to mechanical and generation losses  $\eta$ . Thus,

$$\bar{\eta}_{ov} = C_p \cdot \eta$$

$\eta = 0.5$  was used in this work, and the aerodynamic performance of the rotor is given as:

$$C_p = \frac{\bar{\eta}_{ov}}{\eta} = \frac{0.111}{0.5} = 0.222$$

Based on the above power coefficient (0.222) and theoretical coefficient, and utilizing the power equation, the respective power-wind

velocity relationship have been determined and tabulated as in table 4.2.

**Table 4.2** Theoretical and Actual Power-Wind Velocity Relationship

S/No	Velocity (m/s)	Actual Power (W)	Theoretical Power (w)
1	3	25.97238	69.3765
2	4	61.56416	164.448
3	5	120.2425	321.1875
4	6	207.77904	555.012
5	7	329.94542	881.3385

**5. Conclusion**

It can be concluded that the rotor achieved an aerodynamic efficiency of 0.222. This is not up to the Betz limit (0.593) because of the fact that there were losses in power due to spillage, slight vibration due to unbalance forces and errors during manufacturing and the actual wind speed must be less than the wind speed which was taken at Zaria

aerodrome due to wind obstructions by structures during testing.

**6. Recommendations**

Best manufacturing techniques should be used and ensure excellent machine balance. Mean of acquiring the actual wind speed at the site of testing is recommended to ensure accurate prediction of the performance

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