Development of a Small-Scale Vertical Axis Wind Turbine for Generation of Compressed Air for Pneumatic Systems

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Abstract

This work presents the development of a cost effective vertical axis wind turbine for generation of compressed air using locally sourced materials. The design of the wind turbine takes into consideration the reduction in the weight and size of the turbine thereby lowering production and installation costs. This increases the efficiency by increasing the resistance from dynamic loads and reduction of acoustic noise discharge. The following locally sourced materials were employed for the development of the wind turbine compressed air system: acrylonitrile butadiene styrene, teflon, polyethylene terephthalate, mild steel, rubber and wood filings. The blade design is of the form airfoil shape of NACA 2412 type typical of air crafts wings with a chord of 50 mm and utmost camber of 2% sited 40% (0.4 chords) from the leading edge and utmost thickness of 12% of the chord. The aerodynamic properties include angle of attack which is 2.2° and the utmost twist angle which is 25.66°. From the performance evaluation, maximum tip speed ratio of 0.9 was achieved as well as power output generation of approximately 14 watt at 10.2 m/s wind speed. The findings of this project identify compressed air energy storage as a viable alternative to chemical energy storage generated from wind turbines. The developed turbine will contribute significantly to the effective conversion of wind kinetic energy into pressure energy as opposed to electrical.

Keyword: Airfoil, Angle of Attack, Aerodynamic, Compressed air, Dynamic load

1.Introduction

Wind has been one of the major sources of power for over a century, with significant designs termed as wind mills, fabricated from wood with primary aim of pumping water or grinding [1]. The cumbersome design was substituted a century ago with a fossil fuel adopted engines and the incorporation of distributed power network [1]. A good knowledge of aerodynamics and furtherance in the field of advance materials, most especially polymers, have paved way to the return of energy from the wind in the mid-20th century [1]. Power from the wind popularly known as wind turbine are frequently aim at electricity generation [1]. Power generation through wind energy technology is still at it modest level globally, despite the level of availability [2]. Not more than four countries in Europe generate approximately 10% of their electricity from wind [2]. Perhaps the most unpleasant cases are found among the developing nations such as Somalia and Malawi, despite gifted with abundance of wind resources, are still at the lowest level on the ladder of electricity generation via wind energy[3, 4]. However, this is caused by the existing model of wind energy generation, one that depends increasingly on massive wind conversion machines[4] which arose due to industrial revolution while trying to process fossil fuels of different sources [5]. This system was made worse by the introduction of the conventional horizontal-axis wind turbines that need to be distance so as to prevent aerodynamic hindrance and fatigue loading due to interference with the wakes of adjacent turbines [6]. This demand has necessitated the system of wind energy to move towards remote location, including offshore site, rather than the high energy demand areas [6]. It also

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contributed to the use of very big wind turbines in order to lower the inefficiency of the wind farm by accessing the much availability of wind resources at high altitudes. Wind turbines have been categorized according to the positioning of the shaft and axis of rotation. A turbine is known as Horizontal Axis Wind Turbine when the shaft is in horizontal position parallel to the ground while for a Vertical Axis Wind Turbine, the positioning of the shaft is normal to the ground. The two categories come with different design of rotor with each having its supportive features [6]. Problems of low tip speed ratio, uneasy to control speed of the rotor and the notion of the system to be of not self-starting put a limit to the continued development of vertical axis wind turbine[7]. Nevertheless, its needs no adaptation for face the wind, and heavy generators can be position on the ground to minimize loads. In view of these, the development is not totally phase out in the future. A uniqueV-form vertical axis wind turbine rotor design is presently been investigated which exploits these complementary attributes [8]. Apart from the challenges that were faced in the former design of vertical axis wind turbine, horizontal axis wind turbine gain more popularity due to the increase in the controlling of the rotor through the pitch and yaw control. Therefore, horizontal axis wind turbine becomes the major design by the leading large-scale turbine manufacturers. Research activities on alternative turbine technologies are springing out due to interest in wind energy provision in unique environment; examples are rotors for deep-water off-shore locations with floating foundations [9] and constructing augmented wind turbines (roof installations) in the civilized environment [10, 11]. In these cases, lift driven Vertical Axis Wind Turbine (VAWT) technology provides numerous benefits, including insensitivity to yaw angle, minimum noise as a result of low tip speed ratios and, for bigger turbines, ground positioning of mechanical and electrical heavy parts [12]. There is a plurality of VAWT designs (for example H-type, V-type, Troposkien-type and Gorlov type with helical blades, as shown in Figure 1) that brings about a form of complexity in the general VAWT design criteria, also considering the potential optimization of such geometries [13].

![Figure 1: Possible variants of Darrieus VAWT: H-type (a), V-type (b), Troposkien type (c), and Gorlov (helical type, d) [14].](image)

The project is aimed at the development of a small scale vertical axis wind turbine for generation of compressed air to actuate low power pneumatic systems using locally sourced materials. The objectives are to have a design with considerable low tip speed ratio and able to generate a sufficient power output. This is significant in the sense that it will contribute greatly to the reduction of energy production cost, reduce pollution generated from other alternative energy sources and the compressed air energy storage will provide a safe and cheap means of generating and storing of compressed air for a longer period of time.
2. Materials and Method

The study involved the identification of the essential materials and design considerations. These were followed by the conceptual and detailed design of the machine using existing design theories.

2.1 Materials Selection

Material properties such as bulk density, cost, availability, high strength to weight ratio, resistance to humidity, machinability, high fatigue and impact strength were duly considered before selection for the fabrication.

2.1.1 Materials for blades

Blades are the airfoil shaped component attached to the shaft. They serve as the mechanism of converting wind energy into lift in order to create torque. They are made with light weight and easily machinable Acrylonitrile butadiene styrene (ABS) polymer filled with wood chips for overall rigidity and reinforced with 3mm brass rods for increased impact strength. Mechanical and chemical properties such as high strength to weight ratio, good machinability, high resistance to humidity, high resistance to ultraviolet rays, high fatigue and impact strength were considered in selection.

2.1.2 Materials for the Shaft

The shaft is the cylindrical component used to transmit motion and power from the turbine to the impeller. It also serves as the point of attachment of the airfoil blades. It is made from teflon due to its high strength, low density, and high resistance to corrosion while steel is used for the impeller. The dimensions of the turbine shaft are 16 mm diameter and 500 mm length, while that of the impeller are 6 mm diameter and 130 mm length. It is designed in such a way that it is light enough to rotate freely whilst being strong enough to provide torque for air compression.

2.1.3 Materials for the Hub

The hub was fabricated from 2.5 mm cylindrical steel rods. Then it was installed as a pair with 90 degrees angular spacing along the horizontal plane, and 30 mm linear spacing along the vertical axis of the turbine shaft. Each rod was 2.5 mm diameter and 170 mm length. 2.1.4 Material for the Impeller

The impeller is made from Polyethylene terephthalate, due to its finishing, low density, high fatigue strength, optimum flexural rigidity and heat resistance.

2.1.5 Material for the Compressor Housing

The compressor housing was also made from a composite material which included light weight and easily machinable Acrylonitrile butadiene styrene (ABS) polymer which was filled with wood chips for overall rigidity and reinforced with 3mm brass rods for increased impact strength.

2.2 Engineering Design of Components of the Machine

The major components of the turbine-compressor unit are described below:

2.2.1 Design of Turbine Blade Unit

The blade design is of the form airfoil shape of NACA 2412 type typical of air crafts wings with a chord of 50 mm and utmost camber of 2% sited 40% (0.4 chords) from the leading edge and utmost thickness of 12% of the chord. The aerodynamic properties include angle of attack which is 2.2° and the utmost twist angle which is 25.66°. Four-digit series airfoils by standard have utmost thickness at 30% of the chord (0.3 chords) from the leading edge.
2.2.2 Design of the Turbine Compressor Unit

The compressor is a unit that operates subject to transitional and turbulent wind speed conditions. The isometric view of the compressor is displayed in figure 4. The vertical axis wind turbine transforms wind motion to purely rotational motion, by means of its airfoil blade design which generate lift upon impact of wind, propelling the blades forward in a constrained circular motion. Upon the rotation of the compressor impeller, suction is developed and low pressure air is forced into the compressor via the face of the impeller. The low pressure air flows through the air passage formed by the blades of the impeller which rotate with speed twice that of the wind turbine. As the air moves towards the tip of the impeller, momentum is gain, and there is increase in the static pressure. From the tip of the impeller, the air flows into a stationary diffuser where it decelerates and as a result the dynamic pressure drop is converted into static pressure rise, thus increasing the static pressure further. From there, the air flows to the volute casting, where more velocity changes to static pressure due to the divergent shape of the volute and good quantity of pressurize air leaves the compressor through the volute casting. It should be noted that the momentum gained was due to high speed of the impeller transferred to the air with the air passage. The increase in the static pressure was due to self –
compression caused by the centrifugal action. The compressed air is stored in a pressure tank, which allows air only through the inlet. The diagrams of the turbine compressor unit and its working principle are shown in figure 5 and 6.

Figure 4: Isometric View of the Compressor

Figure 5: Drawing of Turbine and Compressor
2.3 Design Analysis and Theories

In the design of this energy unit, various criteria which are used for turbine-compressor units are as follow:

2.3.1 Determination of Wind Power Available

Power is defined as:

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

Where:

- \( P \) = Wind Power
- \( \rho \) = Air Density
- \( A \) = Turbine blade Swept Area
- \( V \) = Wind Velocity

The length of the blade is used to determine the Swept Area \( A \), from the expression of area of a circle in Equation 2:

\[ A = \pi r^2 \]

Where \( r \) is the length of the turbine blade.

Putting the Betz limit into account, the turbine power efficiency is 0.59. This connotes that the turbine could account for 59% of the energy conveyed by wind. This is expressed as:

\[ C_{\text{max}} = 0.59 \]

The power coefficient should be accounted for in equation 1. Therefore, available power by the wind turbine is expressed as equation 4:

\[ P = \frac{1}{2} \rho AV^3 C^3 \]

2.3.2 Determination of Power Extracted

The power extracted by the turbine is given by equation 5 as:

\[ P_r = \tau \omega \]

Where \( \tau \) is the blade torque and \( \omega \) is the angular velocity.
The efficiency of the wind turbine is given as the ratio of the power extracted \( P_r \) to power available \( P \).

### 2.3.3 Determination of the Nature of Wind Speed

The speed of the wind is also accounted for during turbine blade design. The wind speed sets the Reynolds Number expressed by equation 6:

\[
Re = \frac{\rho u c}{\mu}
\]

Where \( u \) is the wind speed, \( c \) is the length of the blade cord and \( \mu \) is the air dynamic viscosity. The value of the Reynolds number is proportional to the stall coefficient of lift for specific airfoil shape, but inverse to drag for a given angle of attack.

### 2.3.4 Determination of Drag and Lift

The airfoil generates the forces of drag and lift that rotates the turbine. The forces are expressed in equations 7 and 8 with coefficients of lift \( Cl \) and \( C_d \)drag respectively.

\[
L = \frac{1}{\rho V CS^2_l}
\]

\[
D = \frac{1}{2\rho V CS^2_d}
\]

The glide ratio, expressed in equation 9, determines the performance of the wind blade.

\[
\frac{L}{C_l} = \frac{D}{C_d}
\]

Where \( \rho \) is the Air density, \( S \) is Span of airfoil, \( v \) is air velocity and \( c \) is Chord of the airfoil.

### 2.3.5 Chord Distribution

The chord distribution, expressed in equation 11 influences the reliability of the turbine blade and also account for the loss in energy level due to wind vortices

\[
c = \frac{5.6R^2}{iTSR_i}
\]

Where, 
\( i \) is theno of teeth
\( C_l \) is the maximum lift coefficient \( r \) is
the radius at a point of computation
\( TSR \) is the tip speed radius at particular radius \( r \)

### 2.3.6 Blade Twist

Assessment of the power coefficient derived at each segment of the blade determines the design of the blade twistas expressed in equation 12

\[
\tan \phi = \frac{2}{11 iC}
\]
The tip speed ratio is given as \( \lambda \). It determines the tip speed of the blade as expressed in equation 13.

\[
\text{Blade tip speed} = \text{TSR} \times \text{wind speed}
\]

The Rated Revolution Speed

The rated revolution speed can be derived from equation 14

\[
\text{rpm} = \frac{60 \times \text{VTSR}}{6.28}
\]

2.4 Design Considerations for the Impeller

The figure 7 shows the diagram of the air velocity of the impeller. The amount of torque \( \tau \) required for the rotation of the impeller is equal to the rate of change of the angular momentum of the air, provided it flows radially through the blade as expressed by 15:

\[
\tau = \frac{m r v^{2}}{2} \omega
\]

The power input to the impeller \( P \) is given by equation 16.

\[
P = \tau \omega = mr v^{2} \omega = mu v^{2} \omega
\]

Where

- \( m \) = Air mass flow rate
- \( r_{2} \) = External radius of the impeller blade
- \( v_{1,2} \) = Tangential component of the air velocity at impeller exit
- \( u_{2} \) = Tip speed of the impeller blade
- \( \omega \) = Angular speed in radians/s
- \( r_{2} \) = Radius of the impeller blade

Figure 7: Velocity Diagram of the Impeller

The normal component velocity, \( V_{n,2} \) of air at the impeller exit is shown in figure 7. This is proportional to the volumetric flow rate. The tangential component \( V_{t,2} \) is expressed in terms of the tip speed \( u_{2} \), normal component \( V_{n,2} \) and the blade angle \( \beta \) in equation 17:

\[
\sqrt{V_{t,2}^{2} + V_{n,2}^{2}} = \frac{u_{2}}{ \cot \beta}
\]
\[ V_{t2} = u \ V_{2} - \nu \cot \beta = u_{2} \ (1 - \frac{u_{2}}{u}) \]

Therefore, the input power \( P \) to the impeller is given by equation 18:
\[ P = m \ u \ V_{2} \cot \beta - u_{2} \]

For a reversibly and adiabatic compression process, then input power is given as equation 20:
\[ W_{c} = m \ h \ (e - h_{c}) = m \int_{\rho l} \ V \ d \ p_{c} \]

Relating equations 19 and 20 in equation 21:
\[ \frac{p_{c} \ W_{c}}{p_{2}} = (\omega r_{2})^{2} \]

Wherefore, at any given condition of suction, the pressure ratio is directly related to diameter of the impeller blade as well as rotational speed of the compressor.

3. Performance Evaluation
The performance evaluation was based on the annual power output and variation of Tip Speed Ratio. Determination of the velocities profile was carried out by measurement of the air flow along the diameter of the shaft taking from the range of 5 to 14 m/s and the turbine power curve was drawn by comparing the torque produced with the corresponding rotational speed. The impeller rotational speed is varied with the wind speed as well.
1. Determination of Swept Area
Distance of blade from central axis = 0.17 m

\[
\text{Swept Area } A(\theta) = \pi(0.17)^2 = 0.0908 \text{ m}^2
\]

2. Determination of Power Output
The maximum level of efficiency a wind turbine could attain according to literature is 59%. If the air density (\(\rho\)) is assumed to be 0.93 kg/m\(^3\), and the turbine and generator efficiencies are about 0.35 and 0.9 respectively. The power output produced at wind velocity of 5m/s is given by the equation:

\[
P = \frac{1}{2}(0.93)(0.09)(5)^3(0.35)(0.9) = 1.6478 \text{ W h}
\]

3.1 Result and Discussion of Annual Power output
The results shown in the Table 1 are for 0.09 m\(^2\) swept area of turbine. The power output is a function of the air flow directed from the wind turbine to the compressor via impeller blade. Power output of 168W/h per year was reached at the velocity of 10.2m/s, approximately equivalent to 6.79 m/s in the 0.09 m\(^2\) turbine compared to analytical data found in literature. Figure 8 shows the variation of wind speed to turbine and impeller speed. There is a direct relationship between the turbine and wind speed. The impeller speed is twice that of the turbine due to the ratio of the gear of 1:2, neglecting the air loss. The curve follow the same trend as the result obtained in a similar demonstration by Jamanun et al [17]. In figure 9, the higher the wind velocity, the higher the energy output. This is due to the built momentum that led to the generation of higher static pressure as a result of wind motion been transformed to rotational motion in the turbine. This result is also similar to that of Ajao [18].

Table 1: Experimental Results of Power output

| Turbine Speed Rps | Impeller Speed Rps | Wind Velocity m/s | Torque force Kg. F | Power output w/h | Annual power output w/h per year |
|-------------------|--------------------|-------------------|-------------------|-----------------|----------------------------------|
| 1.7               | 3.4                | 5.0               | 0.4               | 1.6478          | 19.7736                          |
| 1.9               | 3.8                | 5.5               | 0.5               | 2.1932          | 26.3184                          |
| 2.1               | 4.2                | 6.2               | 0.8               | 3.1418          | 37.7016                          |
| 2.4               | 4.8                | 7.0               | 1.2               | 4.5217          | 54.2604                          |
| 3.0               | 6.0                | 7.7               | 1.7               | 6.0184          | 72.2208                          |
| 3.9               | 7.8                | 9.0               | 3.0               | 9.6102          | 115.3224                         |
| 4.2               | 8.4                | 9.5               | 4.0               | 11.3026         | 135.6307                         |
| 4.6               | 9.2                | 10.2              | 5.0               | 13.9896         | 167.8756                         |
3.2 Result and Discussion of Tip Speed Ratio

Figure 10, shows the relationship between impeller Tip Speed Ratio ($\lambda$) and air speed that flows across the impeller blade. TSR of 0.67 was obtained at air speed of 5.0 m/s and this continuously increased as the air speed increases. The Tip Speed Ratio determines the performance of the compressor, i.e., the ability of the compressor to compress maximum air that flows across the impeller. The higher the impeller speed, the higher the Tip Speed Ratio
[19]. Therefore, impeller must be designed to operate at optimum TSR in order to compress as much air as possible.

Figure 10: Variation of Impeller Tip Speed Ratio ($\lambda$) and Wind Speed (m/s)

From the figure 10, the maximum TSR of 0.9 was obtained at maximum air speed of 10.2 m/s. the curve is similar compared to that obtained in [17], but bit lower due to possibly the design of the swep area of the turbine which invariably affect the TSR of the impeller [17] [19] or the weight of the impeller rotor too big to rotate faster [17]. At wind speed of 10.2 m/s, a flow rate of 2.5 liters per minute was measured. As pressure output was not measured theoretically based on flow rate data from the literature, the device would inflate a bicycle’s tire to 30 psi in approximately 12 minutes

4. Conclusion
The development of vertical axial wind turbine that can be adapted for small size pneumatic system has been achieved. The design and configuration of the turbine blade gave an optimum swep area for reasonable amount of wind power to be extracted to produce considerable power output. The maximum Tip Speed Ratio of the impellerjustified good performance of the compressor to be able to compress air up to 30 psi for pneumatic purposes.

5. Recommendations
From the design of the Turbine, a variable speed controller in form of a gear box can be installed in order to maintain constant speed.

The Gorlov turbine blade structure ca be employed to give constant velocity and self-starting capabilities to the system.
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