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Development of a horizontal three bladed windmill with vortex tubes

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ABSTRACT

Researchers have been continuously searching for the most readily available means of producing electricity without any negative effect on the environment. Renewable source of energy like solar energy, hydro electric energy, biomass and wind energy has been considered as the alternative. Wind energy among others is rated the best renewable sources of energy because it's level of environmental friendliness. In this paper, a horizontal windmill was designed, fabricated and its performance evaluated with two types of vortices and without a vortex. The component parts of the mills are towel, blades, shafts, base, tail vain and vortex. During the design of the windmill, consideration was given to the size, area of the blade and the blade material that produce maximum speed. The performance evaluation was carried out to compare the performance of the mill with the solid vortex, gap vortex and without vortex. The result of the evaluation reflects that the solid vortices have the highest wind speed irrespective of time of the day and with an optimum wind speed of 5.04 m/s. Also, the wind mill performed at a higher efficiency with the vortex compare to when it was running without vortex.

1. Introduction

There has been increasing awareness that emission from fossil fuel sources is the cause of global warming and their consumption is associated with environmental pollution [1-3]. Also, electricity is very important in economy development of any nation; thus, led to continuous search for alternative means of producing electricity without any side effects on the environment. Renewable source of energy meets such requirement [4].

Solar energy is readily available and performs optimally during the day. Hydro electric energy is only available source of electricity in the country but cannot be supplied to some remote area of the country and its generation is not enough to satisfy the countries requirement. Geo thermal is another source of renewable energy but it produces greenhouse gas beneath the earth surface, which will possibly drift to the surface of the atmosphere and this emission is associated with silica and sulfur dioxide. Likewise, the reservoirs contain toxic heavy metals which include mercury [5].

Biomass gas energy is generated from organic materials, animal or plant waste which is burnt to provide energy; though it is a renewable energy source but its initial cost is

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high, it occupies space and also generates greenhouse emission [5, 6].

Wind, a natural resource, is the air in motion being freely available in space and moves at varying speed depending on the site meteorology [7]. It is a form of energy, dependent on the Sun's asymmetrical heating of the Earth's surface; hence, initiating temperature differences that create pressure and density disparities in the atmosphere. The discrepancy in heating is typically caused due to the diverse heat capacities of different materials being heated by the Sun as observed in the daily land and sea breezes in coastal region [8].

Windmill is a machine that is utilized to harvest kinetic energy of the wind that blows over the blade's rotor assembly causing it to rotate on a shaft [9]. Ojosu and Salawu [10], studied the wind speed data observed during the period (1951-1975) for 22 stations across the country and resolved that Sokoto (Northern Nigeria) has an annual mean wind speed of 3.92 m/s with 5.12 m/s in the month of June. However, lot of work has been done on the exploration of small-scale wind power conversion systems [11-17]. As a consequence, there is the need to examine their prospect and viability in low wind regions of Nigeria [18]. Due to low wind speed problem in most parts of Nigeria (Auchi), there is need to increase wind speed in such areas. The overall aim of this paper is to develop a three bladed horizontal windmill with vortex tubes.

2. Materials and Methods

2.1. Design Calculations

Design for swept area of the turbine: The swept area of a wind turbine can be computed from the length of the turbine blade using the equation (1).

$$A = \pi r^2 \quad (1)$$

Where, the radius, r is equal to the blade length (shown in Fig. 1), the diameter of the shaft can then be obtained if the area is known.

The power in the wind: The power in the wind is computed using equation (2).

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

Where, V is the velocity of wind at the blades, ρ is density of the air, and A is the area of the blades. Maximum extractable power (P_{max}) from wind is given as:

$$P_{max} = \frac{16}{27} P_{w,} \quad (3)$$

$$P_{max} = \frac{16}{54} \rho A V^3 \quad (4)$$

The power coefficient, C_p varies with the tip ratio of the turbine according to equation (5).

$$\text{Tip speed ratio} = \frac{blade\ tip\ speed}{Wind\ speed} = \frac{\lambda}{U_o} \quad (5)$$

$$\text{Blade tip speed} = \frac{Rotation\ Speed\ x\ \pi D}{60} \quad (6)$$

Where, D is the diameter of the turbine.

But the actual power developed by a wind turbine is a factor of the tip speed ratio [19]. As a tip speed ratio of high-speed wind turbine is 8 times that of the incoming velocity, the C_p corresponding to the tip speed ratio will be 0.35 (Fig. 2). Therefore, the practical power extractable from the wind is:

$$P_p = 0.35 \times \eta_t \times P_{max} \quad (7)$$

Where, η_t is the transmission efficiency; taking a transmission efficiency of 56% [20]:

$$P_p = 0.35 \times 0.56 \times P_{max} = P_p = 0.196 P_{max} \quad (8)$$

The energy can be calculated using the following equation

$$Energy = power \times time \quad (9)$$

For this turbine, the $P_p = 0.196\, P_{max}$ but, $Chord\ length = 1.5\ m$, $Rated\ speed = 4.5\ m/s$, $Blade\ thickness\ (t) = 0.0008\ m$, $Air\ Density\ (\rho) = 1.23\ kg/m^3$. Substituting the value for blade length as the radius of the swept area into equation (1):

$$A = \pi r^2 = 7.07 m^2.$$

$$P_w = \frac{1}{2} \times 1.23 \times 7.07 \times 4.5^3 = 396.21\ W.$$

$$P_{max} = \frac{16}{27} \times P_w = 0.5925 \times 396.21 = 234.75\ W.$$

From equation (8):

$$P_p = 0.196 \times 234.75 = 46.01 W.$$

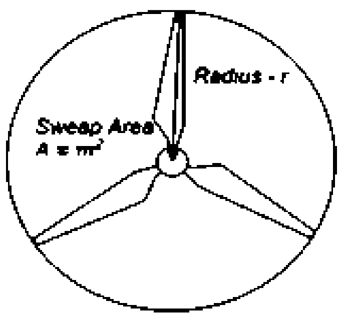

Fig. 1 Swept area.

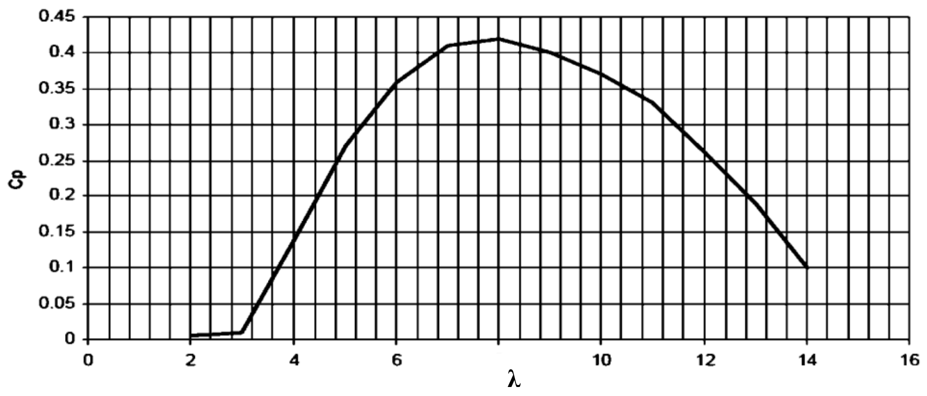

Fig. 2 Cp vs λ curve for wind turbine [21].

$Mass\ of\ blade\ = density \times volume$

Density of mild steel = $7800kg/m^3$, Volume of the blade = $b \times t \times l$ = $2.40 \times 10^{-4}\, m^3$; where, *b* is the breadth, *t* is the thickness, and *l* is the length.

$Mass\ of\ blade\ is = 7800 \times 2.40 \times 10^{-4} = 1.87\ kg$

$Actual\ mass\ of\ the\ blade\ = 0.935\ kg$

$Mass\ of\ hub\ = 2\ kg$

Considering the mass of the hub with respect to that of the blade x mass reduction ratio 1:2 will be used to balance the weight.

Therefore, the actual mass of blade is $1.87 \times 0.5 = 0.935\ kg$.

Weight of blade = $9.81 \times 0.935 = 9.17kg$

Total weight of turbine three blades is $9.17 \times 3 = 27.52\ kg$

Tensile strength of blade: It is deduced using equation (10).

$$Tensile\ strength = b \times t \times tensile\ stress \quad (10)$$

Taking the tensile stress of steel as $250Mpa$, tensile strength= $0.210 \times 0.0008 \times 250 \times 10^6 = 42\ kN$. Taking a factor of safety of 2.5:

Working strength = $\frac{42}{2.5} = 16.8\ kN$

As this value of tensile strength is well below the tensile strength of mild steel, which is about $430\ MP_a$, the blade can withstand this force safely.

Rotational speed is deduced as follow:

$$T_s = \frac{V_{tip}}{V_I} \quad (11)$$

$$V_{I} = \frac{2}{3}V \quad (12)$$

Where, T_s is the tip speed ratio, V_{tip} is the velocity at tip, V_I is the upward velocity, and V is the undistributed wind velocity.

As the tip speed ratio is taken as 8; therefore,

$$V_{tip} = \frac{16}{3}V \quad (13)$$

Angular velocity if the wind turbine is related to velocity at the tip of the blades

$$V_{tip} = w \times r \quad (14)$$

So, the angular velocity at the cut-in speed, $V_c = 2.5m/s$ is

$$\frac{16}{3} \times 2.5 = \omega \times 1.5$$

$$\omega = 8.89\ rad/s$$

Rotational Speed corresponding to this Angular Velocity, N_C

$$N_c = \frac{60 \times \omega_C}{2\pi} = \frac{60 \times 8.89}{6.284} = 85rpm \quad (14)$$

Angular velocity at rated speed of 4.5 m/s

$$\omega_r = \frac{16 \times 4.5}{6} = 12 \text{ rad/s}$$

Rotational speed corresponding to this velocity $N_r\ is$

$$N_r = \frac{60 \times 12}{2\pi} = 114.68\ rpm \quad (15)$$

Angular velocity at cut-out speed, $V_{co} = 25m/s$

$$\omega_{co} = \frac{16 \times 25}{6} = 66.66\ rad/s \quad (16)$$

Rotational speed corresponding to this velocity $N_{co}\ is$

$$N_{co} = \frac{60 \times 66.66}{2\pi} = 636.54\ rpm \quad (17)$$

Maximum Centrifugal force (F_c) acting on the blade: As the F_c acting on the blade occurs at cut-out wind speed of 25 m/s

$$F_c = m \times r \times (w_{co})^2 \quad (18)$$

$$= 0.932 \times 1.5(66.67)^2 = 6.233\ kN$$

As the working tensile strength (allowable strength) = $16.8\ kN$, the calculated centrifugal force is well below the prescribed limit of 6.23

kN. Therefore, the blade can withstand the centrifugal force safely.

Total axial force acting on the turbine: The total axial force (F_t) acting on the turbine is given by:

$$f_t = \frac{\pi}{9} \times \rho \times D^2 \times (V_1)^2 \quad (19)$$

For the axial force to be a maximum, the upward velocity V_l is taken to be equal to the cut-out wind speed V_{CO}

$$f_t = \frac{\pi}{9} \times 1.23 \times 1.5^2 \times (25)^2$$

$$f_t = 603.6N = 0.603\ kN$$

Force acting on the blade: Force acting on the blade is the lift force, f_L and the drag force, f_D.

$$f_L = C_L \times \frac{1}{2} \times A_b \times V_r^2 \times \rho \quad (20)$$

$$f_D = C_D \times \frac{1}{2} \times A_b \times V_r^2 \times \rho \quad (21)$$

Where, V_r is the relative velocity, A_b is the area of the blade, C_L and C_D are the coefficient of lift and drag respectively.

Transmission Shaft and Rotor Shaft: According to America Society of Mechanical Engineer (ASME) code for design of transmission shaft, the maximum permissible shear stress may be taken as $56\ mPa$ for shaft without allowance. The equivalent torque, T_e is obtained as:

$$T_e = \frac{\pi \times \tau \times d^3}{16} \quad (22)$$

Where, shear stress, $\tau - 56\ mPa = 56\ N/mm$; mass of 3 blades = $3 \times 0.9828 = 2.94\ kg$; mass of hub $= 2\ kg$; mass of 3 blades and hub = $2.94 + 2 = 4.94\ kg$; weight of one blade = $0.9828 \times 9.81 = 9.64\ kg$. Also, weight of 3 blades is $9.64 \times 3 = 28.92kg$; weight of 3 blades and hub, W = $2 \times 28.92 = 30.92\ kg$; length $(L = 50\ mm)$.

$$M = W \times L \quad (23)$$

$$M = 30.92 \times 0.05 = 1.55\ Nm$$

Also,

$$T = \frac{P \times 60}{2\pi N} = \frac{35.86 \times 60}{2 \times 3.142 \times 114.60} = 2.987$$

$$T_e = \sqrt{M^2 + T^2}$$

$$= \sqrt{1.55^2 + 2.987^2}$$

$$T_e = 10.430\ Nm$$

Where, M is the bending moment, T is the twisting moment or torque and T_e is the equivalent twisting moment.

Design of Shaft Diameter:

$$T_e = \frac{\pi \tau d^3}{16} \quad (24)$$

$$d = \sqrt[3]{\frac{16T_e}{\pi\tau}} = \sqrt[3]{\frac{16 \times 10.430}{\pi \times 56 \times 10^6}}$$

$$d = 9.848\ mm$$

Using safety factor of 2,

$$d = 9.848 \times 2 = 19.69\ mm$$

So, a shaft size of 20 mm diameter was used for the windmill.

2.2. Mode Operation of Machine

The fabricated wind turbine (Fig. 3) is self-starting. The operation of the windmill starts when the wind has reached an average speed of 2.5 m/s and the wind turbine output increases with the wind speed until the wind speed reaches maximum. If the mean wind speed exceeds the maximum operation limit of 25 m/s, the turbine turns away from the wind with the aid of the furling tail until it returns to normal operation.

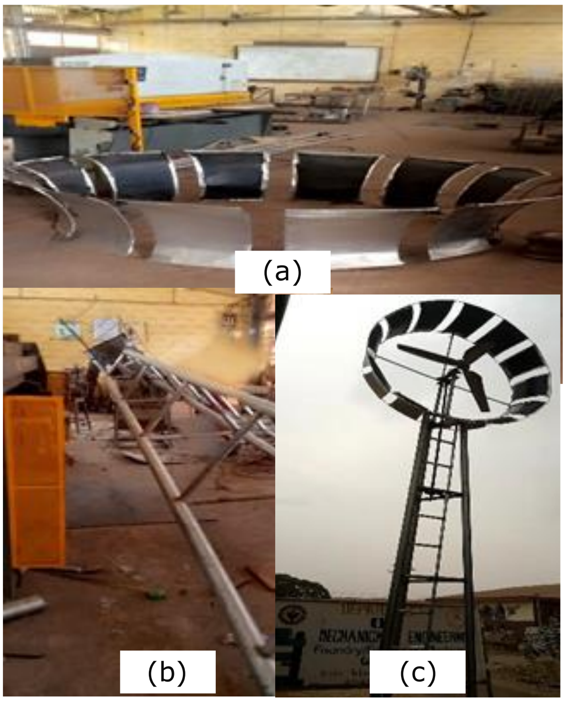

Fig. 3 Pictorial views of the fabricated horizontal three bladed windmill with vertex tubes (a) vertex (b) construction process of the windmill (c) fabricated windmill.

3. Results and Discussion

The result obtained by performance evaluation of the developed three-bladed horizontal windmill with gap vortex, solid vortex and without vortex is shown in Table 1.

Table 1 Values of the windmill speed obtained at different time using different vortex and without vortex.

Time	Velocity of the Windmill (m/s)		
	Gap vortex	Solid vortex	Without vortex
8.00 a.m.	3.00	3.45	2.90
10.00 a.m.	3.24	3.63	2.99
12.00 noon	3.47	4.00	3.10
2.00 p.m.	4.00	4.09	3.20
4.00 p.m.	4.25	4.45	3.47
6.00 p.m.	3.95	4.15	3.20
8.00 p.m.	4.00	4.21	3.23
10.00 p.m.	4.45	4.62	3.46
12.00 a.m.	4.91	5.04	3.85

3.1. Effects of Time and Vortex type on the Windmill Speed

The effects of time and vortex type on the windmill speed are as shown on Fig. 4. The figure revealed that solid vortex has the highest wind speed of 5.04 m/s at about 12 a.m. and it was also observed that at all times the solid vortex has the highest wind speed.

Slight followed by the gap vortex with a wind speed of 4.91 m/s and without vortex has 3.85 m/s same time. In addition, the wind speed increase with time from 8 a.m. to 5 p.m. but tend to decrease at sunset or dust time and increase gradually till 8 p.m. and move speedily till 12 a.m.

3.2. Time Series for Configuration of Gap Vortex Over Time

Fig. 5 shows the relationship between the Gap vortex (m/s) and time (s). It could be deduced from the figure that the speed increases with time from 8 a.m. to 5 p.m. with wind speed of above 4 m/s but reduces between the hours of 5 to 7 p.m. before it further increases.

Fig. 6 shows the relationship between the solid vortex (m/s) and time (s). The figure shows that wind speed increase uniformly throughout irrespective of time with 3.45 m/s at 8 a.m. and increased to 4.45 m/s at 6.00 p.m. and later drop to 4.20 m/s at about 6.00 p.m. to 8.00 p.m. and increased rapidly to 5.04 m/s at about 12 a.m.

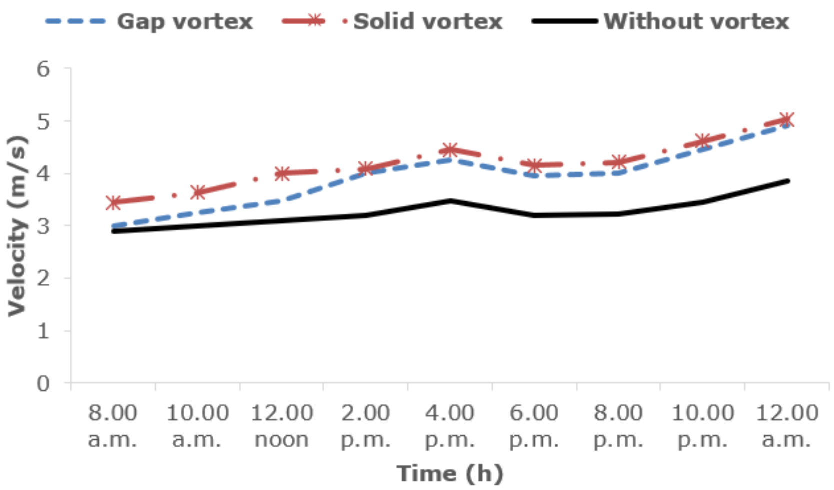

Fig. 4 Effects of time and vortex type on the windmill speed.

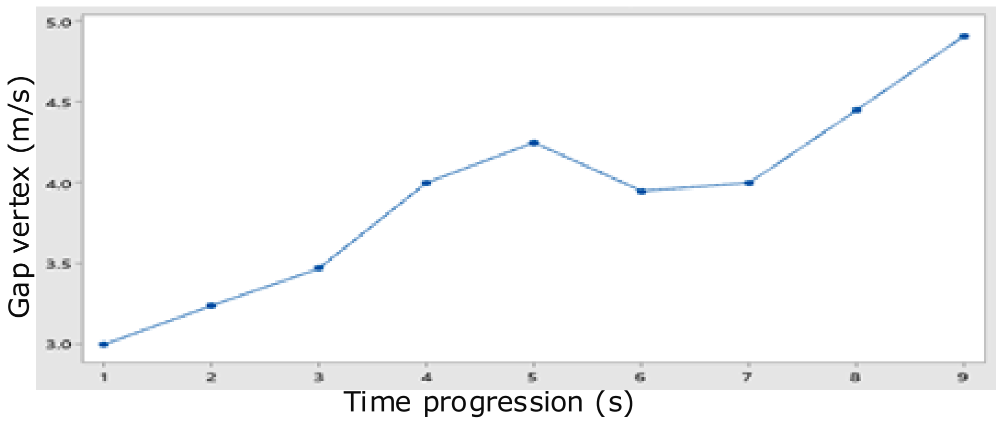

Fig. 5 Time series for configuration of gap vortex over time.

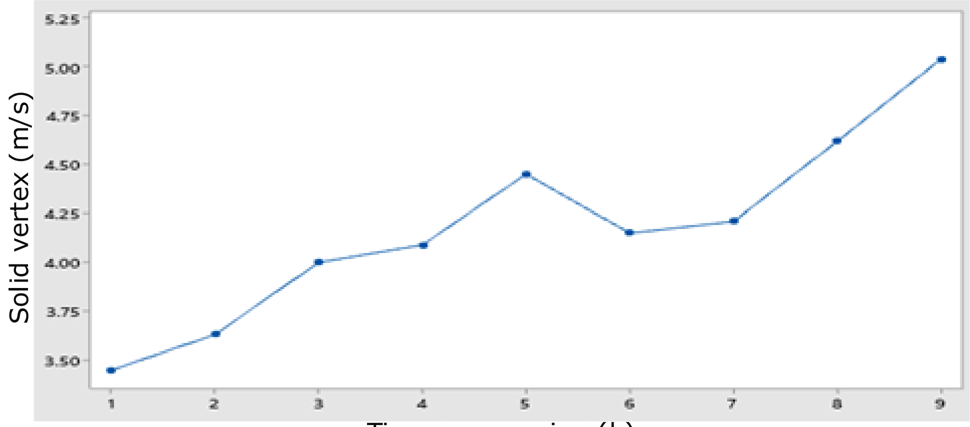

Fig. 6 Time series for configuration of solid vortex over time.

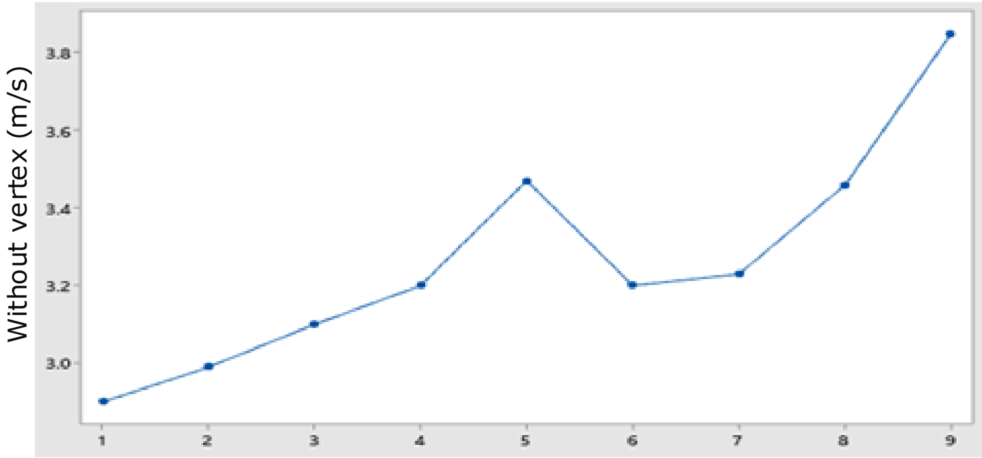

Fig. 7 Time series for configuration without vortex over time.

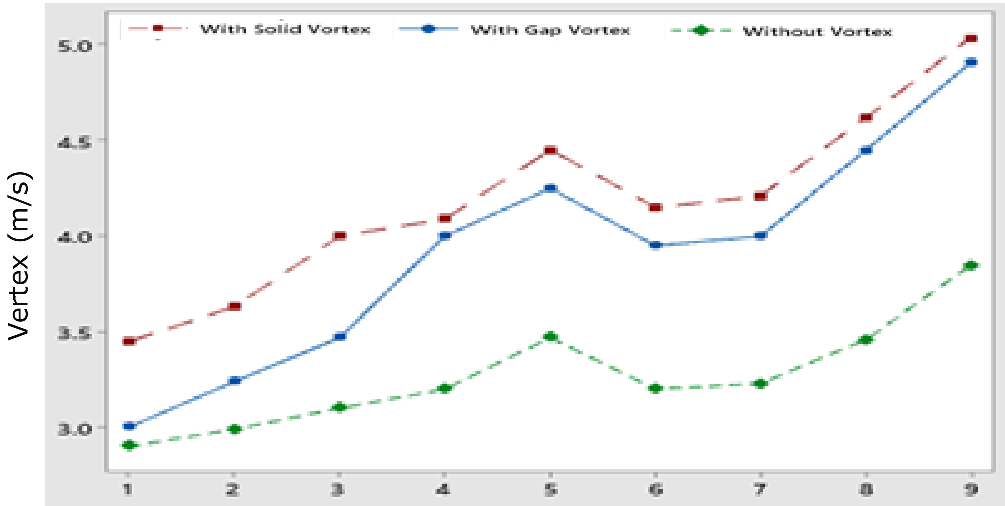

Fig. 8 Time series comparison across all configurations over time.

Fig. 7 shows the relationship between the windmill without vortex and time. The figure shows that at all times the speed was lower than the vortexes but there was still an increase of the wind speed from 2.90 m/s at 8.00 a.m. to 3.47 m/s at about 4.00 p.m. and fall to 3.46 m/s at about 8.00 p.m. and finally move slowly to 3.85 a.m. at 12.00 a.m.

The overall trend (Fig. 8) shows that the vortex generally increases over time. But, the vortex peaks at index 5 (4:00 p.m.) across all configurations, after which the vortex declines momentarily and subsequently continues its upward trend up to 12:00 a.m. This may be attributed to the fact that dusk commences at about that time (4:00 p.m.) and the diurnal temperature begins to fall in order to pave way for nocturnal conditions. This initiation of the fall in temperature affects the ambient air pressure which begins to drop as a result of the reduction in the average kinetic energy (hence collision rate) of air molecules. The subsequent rise in the upward trend of the vortex from 5:00 p.m. and beyond may be attributed to a slight increase in the ambient temperature, as the earth's surface (which has a high heat capacity compared to the ambient air) starts to warm up the ambient air again. Other factors that may contribute to the heating up of the air to increase vortex include increased traffic and other human activities such as the use of electricity generators, which is also prevalent in the evenings toward the night time.

4. Conclusion and Recommendation

A three bladed horizontal windmill with two different vortices tubes (gap and solid) and without vortex was designed, fabricated and evaluated for performance using different types of the vortex and without a vortex using the available wind speed in Auchi, Nigeria. On the site assessment of the output wind speed of the three conditions of windmills operation for a period of 60 days was determine. The result of the evaluation shows that the solid vortex has the highest wind speed irrespective of the time of the day followed by sliding with the gap vortex; these shows that vortex tube of any type has proved to be more efficient and reliable and so it is considered to be the best choice for increasing windmill speed in low wind region like Auchi, Nigeria. In addition, it was observed that the windmill without vortex has a better starting characteristic at low wind speed; therefore, extracting power is easier and faster at a very short period.

The application of wind energy for electrical and mechanical operation in Nigeria could be enhanced and be a better option if the technology is technically improved, specifically the locally-made windmill. The following recommendation is therefore made.

1. Sensor should be attached to the windmill, so that results can be observed at any point in time.
2. The Government should train more personnel on the design, construction operation and maintenance of locally made windmill since it is easy to operate and can be used to solve energy problems in Nigeria.
3. Effort should be geared toward seeking increase in blade efficiency rather than increase in blade size length, which increases cost of the windmill.
4. Wind farm should be created in order to accurately calculate the external wind load acting on the windmill and also for better efficiency.
5. Since the steel blade can easily corrode and increase the weight of the windmill, a composite material with elastic property should be given a consideration.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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