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CONSTRUCTION AND COMPARATIVE STUDY OF A STANDALONE SAVONIUS AND DARRIEUS VERTICAL AXIS WIND TURBINE

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ABSTRACT: *In this work, a Savonius Vertical Axis Wind Turbine (VAWT) and its Darrieus counterpart was designed and constructed based on a preliminary study involving wind pattern analysis of an identified study area, the Usmanu Danfodio University, Sokoto, Nigeria. The turbines were constructed using wood and metals and the resulting blades were field tested under various wind conditions available in the study area. The results of the test were compared in terms of start-up wind speed and their rotor's Revolution Per Minute (RPM) values. The result of this test showed that the Savonius rotor proves to self-start at a wind speed of 2.46 ms^{-1} with a minimum Revolution Per Minute (RPM) of 46 and maximum RPM of 89 at a wind speed of 9.28 ms^{-1}. The Darrieus blade proves to self-start at a higher wind speed of 3.8 ms^{-1} with a minimum RPM of 54 and a maximum RPM of 93 and at a wind speed of 8.9 ms^{-1} under same prevailing atmospheric conditions of the study area. When both standalone results were integrated into a single system, an equivalent of a combined Savonius-Darrieus type of VAWT resulted and for which a reinforcement in RPM was observed. It was recommended that a combined Darrieus and Savonius VAWT when constructed will optimize the high rotational efficiency of Darrieus and the high self-starting capabilities of Savonous VAWT.*

KEYWORDS: Renewable energy, wind turbine, savonius, darrieus, RPM, wind speed

INTRODUCTION

Nigeria is well equipped with various sources of renewable energy such as solar, wind, biomass, hydropower, and ocean waves in addition to fossil fuel sources. Despite all the numerous available energy sources, their resultant contribution is yet to significantly impact and address the massive shortage of power supply (Sambo, 2012). Wind is the thermal movement of air particles and it is an environmentally friendly source of energy that when properly harnessed, has the potential of satisfying the energy needs of people living around areas with high wind potential. It can also serve as a means of mitigating climate change primarily caused by the emission of greenhouse gases, emitted by the burning of fossil fuels. It has been estimated that around 10 million megawatts of energy are available in the earth's wind (GWEC, 2006). But the potential of wind energy can only be reflected in the increase in capacity of wind turbines. As at 2010, the installed capacity of wind energy system in the world is around 194,390 MW (GWEC, 2010).

The average wind speed in Nigeria range from 2 ms^{-1} to about 4 ms^{-1} with the highest average speeds of about 3.5 ms^{-1} and 7.5 ms^{-1} in the Southern and Northern part of the country

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respectively. So, on a nationwide scale, harnessing and electrification of wind energy can only be adequately achieved in few locations such as Gusau, Jos, Kano and Sokoto. Other potential areas for electricity generation are some of the North eastern and North central states with average annual wind speeds in the range of 5-6 ms^{-1}. It was on this note that, the country was rated between 1 to 3 in the Southern state and between 3 to 4 in the Northern state on a Beaufort scale. There is a positive prospect for utilization of wind energy in Nigeria depending on the end use (Adaramola and Oyewola, 2011). Meaning that, there is huge prospect within the country for power generation through wind if associated challenges hindering wind energy technology (WET) advancement are surmounted (Ajayi, 2010).

Statement of the Research problem

It is found that although, Nigeria is blessed with reasonable wind energy resources for power generation, the country is still suffering from high level of epileptic grid power supply which have directly affected development and impinged negatively on economic growth with some parts of the country especially the rural areas lacking access to modern facilities which comes with availability of electric power. Owing to this, the interest in alternative energy sources has increased in recent past. And the potential of wind energy as a source of alternative energy cannot be underestimated. Wind, when tapped from a viable location by wind turbines, converts its kinetic energy into mechanical power, which will in turn be converted into electricity by a generator connected to the wind turbine. There is need to identify a viable study area, carry out wind analysis to ascertain the wind energy potential of the area and to design a suitable wind energy conversion system that will adequately supply electricity all year round.

Aim and Objectives

The aim of this research is to construct a standalone Savonius and a standalone Darrieus vertical axis wind turbine and compare their performance under wind patterns found in the rural area of Usmanu Danfodiyo University Sokoto. In order to accomplish this goal, the following objectives were addressed:

1. Analyze wind speed pattern in a rural environment around the Usmanu Danfodiyo University Sokoto. This was done by gathering data from anemometers at three different heights around the campus.
2. Evaluate various turbine designs of the Savonius and Darrieus type based on the local wind pattern and to select the best for the area.
3. Construct the selected design type using locally available materials.
4. Evaluate the performance of the turbine so constructed by creating an experimental setup and performing tests.

This study is significant because it will reveal the wind speed characteristics of the study area which is a vital information needed for the installation of specific types of wind turbine in terms of required wind speed start-up. Secondly, the RPM of the installed turbine provides a vital information needed for the installation of specific types of generators that will intercept the turbine in terms of RPM specification being appropriate for expected power output.

Study Area

The Energy Research Center, Usmanu Danfodiyo University Sokoto is located at the North Western part of Nigeria, Sokoto State with Latitude $13^{o}1'$N and Longitude 5^{0} $13'$E, 350m above sea level with a yearly average wind speed of 7 ms^{-1}. Sokoto State shares a border with Niger

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Republic and is among the five states in Nigeria that enjoys a lot of average wind speed ranging from 2.5 ms^{-1} to 7.5 ms^{-1}. The wind speed characteristics of Sokoto over a year (2010) is shown in Figure 1.

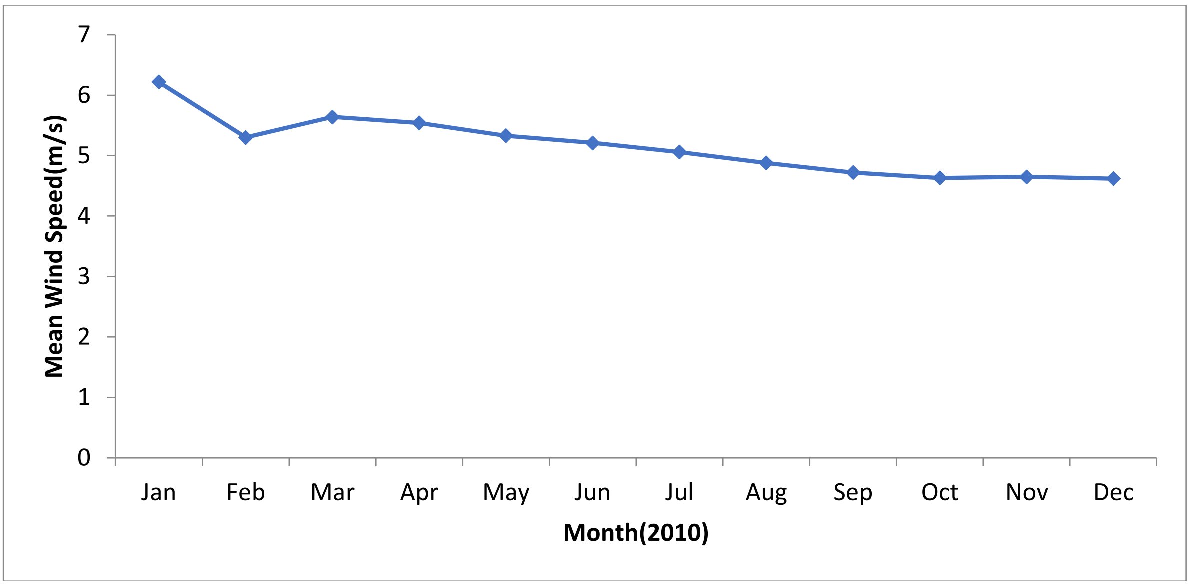

Figure 1: Average wind speed for one year in Sokoto State (Momoh *et al*., 2013).

LITERATURE REVIEW

Turbines are of two types, Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). The vertical axis wind turbines are mostly feasible for places with low wind speed whereas the horizontal axis wind turbines are highly uneconomical. Furthermore, vertical axis wind turbines do not require any yawing device that brings the blades to the direction of the incoming wind, as required in case of horizontal axis wind turbines. Vertical axis wind turbines were first used long time ago in ancient Persia and were only used to grind grain (Cheremisinoff, 1978).

A scientist and engineer in person of S. J. Savonius invented the Savonius turbine in 1922 (Eriksson *et al.*, 2008). But Johnson (1985) wrote that, this Savonius rotors are drag turbines since their tip speed ratio is always less than 1. The concept of Savonius rotor was based on cutting a cylindrical drum vertically from the top to the bottom into two equal halves and then placing the two semi-cylindrical surfaces sideways along the cutting plane (Bachu, 2012). Subsequently, vertical axis wind turbines are always connected to a generator in order to generate electricity from it. So, its design has improved with time and the main shaft is set perpendicular to the direction of wind flow, while the generator is placed at the base of the turbine. This arrangement allows the generator and gear system to be located close to the ground, facilitating service and repair. Vertical axis wind turbines are now applied in offshore wind farms (Holinka, 2012, due to installation and operational challenges, they offer two major advantages which are: lower turbine centre of gravity to improve stability and reduced machine complexity in order to reduce the cost of installing a wind turbine, In order to improve the performance of Savonius rotor, it is important to pay more attention to some of the geometrical factors like overlap ratio and blade gap (Swirydczuk and Kludzinska, 2012).

Jean Marie Darrieus invented and patented the Darrieus vertical axis wind turbine in 1925 and 1931 respectively. His work was re-invented in the late 1960s (Mittal, 2001), But until in late 1960s that attention was drowned to his work, and the aftermath was the invention of the Straight Bladed VAWT or H-Rotor (Eriksson *et al*., 2008) which got its name due to the single horizontal arm supporting its two or more blades (Berg, 1996). Though, VAWT rotors have other different types, Helical Savonius, Eggbeater Darrieus, H-Darrieus, combined configurations of Savonius and Darrieus rotors etc.

Traditionally, Darrieus blades with two or more blades are always having an airfoil design unlike the Savonius but its disadvantage is on the starting torque coefficient which is very low when compared to the Savonius. Which means that, a special motor will be required to start or put the blades in motion since it cannot self-start on its own at a lower wind speed (Kragten, 2004). This is a setback of Darrieus turbine where the Savonius turbine is of obvious advantage. Darrieus rotor is usually a non-self-starting wind turbine but it provides good power coefficient after its cut-in wind speed has been reached.

However, in Nigeria, the interest in windmills started in the fifties and early sixties. Few designs were developed but could not yield expected results. This could be due to intermittency in wind speed around potential localities (Ogbonaiya *et el*., 2007). In order to combat this set back, the challenges in design of a wind turbine should be improved and vertical axis wind turbines should be adopted to represent suitable alternative for harnessing wind power because they accept wind from any direction and can function at a very low wind speed (Akwa *et al*., 2012). Despite all the advantages possessed by vertical axis wind turbine, it is still not gaining popularity because of low efficiency of the Savonius rotor and low starting torque of the Darrieus type wind machines.

Basically, a wind turbine is made up of rotor blades that are installed at the top of high towers, they harvest the energy of the wind by allowing the wind to attack and rotate them, which in turn produces electricity with the help of a generator. Wind technology is improving by the day and this turbine blades are getting larger and more efficient. The reason for maximizing the length of the blades is that, the larger the swept area of the turbine (this is the circle that the turbine produces while spinning) the more wind it will catch and therefore, this increases the energy it can generate. The reason for situating the turbines atop high towers is that, wind speed tends to be higher at altitude and the power contained in the wind is proportional to the cube of the wind speed.

Wind power has expanded rapidly to make a significant contribution to global electricity generation. The World Wind Energy Association has reported a promising yearly growth rates in global wind energy generation but despite these initiatives, in 2009, wind power still only contributes about 1.5% of the global energy generation (WWEA, 2009) and after nine years, the center for climate and energy solutions stated that, wind power has contributed more than 5% of global energy. This shows the rapid growth of wind power (C2ES, 2018).
The Kinetic power of the wind is described by equation (1) as:

$$E_{kin} = {}^{1}/_{2}\, mv^2 \quad (1)$$

where:
E_{kin} = kinetics power [W];

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m = mass flow [kg/s], given by;
m = ρAv (2)
ρ = density of air [kg/m^3];
v = speed of air [m/s];
A = area swept by a wind turbine [m^2];
For a VAWT, the swept area A, is described by:
$A = dh$ (3)
Where;
d = diameter of the rotor [m]; ρ
h = length of the blades [m];
putting equation (2) into equation (1) yields the power in the wind as,

$$P = \frac{dE}{dt} = {}^{1}\!/_{2}\, \rho A V^3 \quad (4)$$

Out of the power captured by equation (4), the maximum power which can be extracted by a wind turbine is given by

$$P_{Kin} = {}^{1}\!/_{2}\, C_p \rho A V^3 \quad (5)$$

where C_p is the maximum power ratio of a the wind turbine given as 0.59.

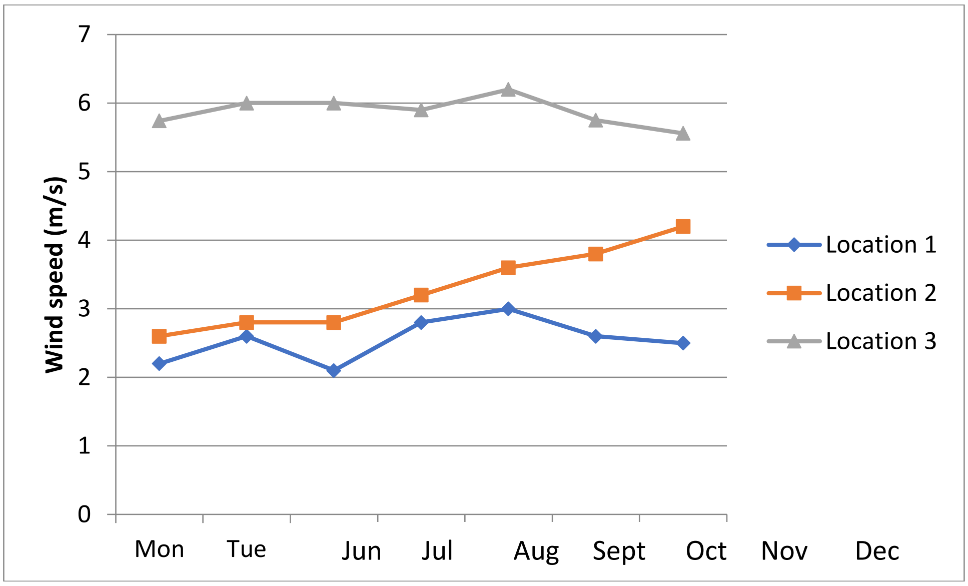
The density of air varies with the height above sea level and temperature. The standard value used for the density of air at sea level is 1.2 kgm^{-3}. Wind power density of a location is the most important parameter to be considered in citing a wind energy conversion system (WECS) as it takes into consideration the wind speed, wind speed distribution and air density.
Since the period of high wind speed coincides with dry season when the northern part of the country is usually dry, the use of wind energy for electricity generation would help alleviate the energy shortage usually experienced due to shortfall in hydroelectricity contribution as a result of low level of water in the Niger River (Momoh *et al*., 2013). However, due to the generally low wind speed in the study area, vertical axis turbines are most suitable. Although the major drawback of vertical axis wind turbines are their low performance coefficients. That is why there are many ongoing researches on vertical axis wind turbines in order to improve their performance. This being the reason this present work is based on Savonius and Darrieus VAWT rotors.

MATERIALS AND METHODS

The method employed in this work is that of field survey given rise to design specification and leading into actual construction and testing.

Field Survey

As part of the field studies for this work, wind data were collected at Usmanu Danfodiyo University, Permanent Site, Sokoto State in order to ascertain the wind speed pattern of the study area. A location free of wind breakers was identified and three altitudes were considered for a period of seven months with the aid of a thermo anemometer. One of the altitudes is at a height of 1.75 m, while the second at the height of 4 m and the third was at a height of 10 m above the ground. The months considered were from June to December which are months associated with lower wind speed values as shown in Figure 1. This is to allow for a worst-case design. The data obtained was downloaded into Microsoft Excel package where the wind speed data was converted to mean monthly wind speed data and plotted against the corresponding months. Figure 2 shows the wind speed distribution at the three altitude for the months of June to December.



Height 1
Height 2
Height 3

Figure 2: The average wind speed at three height over seven months in the study area

It is observed that wind speed was quite low compared to the average wind data analysis of Sokoto State collected for a period of one year shown in Figure 1. Based on the data collected at three different altitudes, altitude 3 of height 10 m was chosen for the research since it has the highest wind speed values and therefore more favorable for the running of wind turbines. The near absence of wind breakers at this height around the site has influenced the wind speed values encountered at altitude 3.

Design/Airfoils Analysis

Qblade software was used to analyze the wind data and to accurately predict how different airfoils would perform under the prevailing wind condition of the area. This increased the possibilities of coming up with an efficient Darrieus turbine blade design. The software was used to select the best blade design that can effectively perform under the prevailing wind condition of the study area. NACA0012 was selected and modified to NACA 0012-34 airfoil after several analysis. The modification was also necessary because NACA0012 cannot operate at a transonic speed since they were only designed with thickness location for lift in mind and not high or low-pressure regions. So, supercritical airfoils are better to reduce wave drag and performs better in high or low pressure regions. To enable efficiency of operation of the blade, the following design specifications were considered: The blade is 2.5m long with a chord radius of 0.26m, the pitch was reduced to 0%, radius 0mm, thickness 0.04m (150%) and the origin as 0%.

Turbine Construction

The following steps are involved in turbine construction: The first step is the construction of the Darrieus blade. The second step is the Construction of the Savonius rotor. Third step is the general assembling of both turbines and finally, the mounting of the turbine.

Construction of Darrieus Blade

The turbine is intended to be a custom design; thus, the major parts were built from design analysis and from raw materials found within the environment**.** The construction of the chosen blade design involves properly and carefully measuring and carving while ensuring all measurement are intact. The Darrieus blade was carved out from a plywood 3 m long. It was accurately measured to ensure that the chord length of the airfoil shape is distributed evenly throughout the length (height) of the blade. To do this, a sheet of tin was placed on the desired airfoil shape. The shape was traced out neatly and cut. The cut-out piece was placed on the wood to make the leading edge on the two sides of the airfoil. All three pieces were then duct taped at the hinged portion to create the entire airfoil. Precautions were taking to avoid termites attack or shrinking of the blade by painting the wood and by placing a weight on top of the wooden blade to ensure the blade does not bend.

Construction of Savonius Blade

The Savonius blade was built out of a metallic drum of diameter 0.5 m and height 0.9 m. The drum was cut into two equal halves and welded to a shaft of 2.9 m long. Another metal was welded round the diameter and length of the Savonius blade to ensure stability of the blade during rotation. The two half drums cut to make the Savonius blade were joined together by placing the half drums side by side, back and front to one another maintaining an overlap ratio of 50 % and then welded to the shaft. The blades were finally painted to prevent corrosion or rust.

Assembling of both Turbines

The auxiliary parts of both turbines which include the rotors, shafts, ball bearings were equally constructed as explained below:

The Rotor

The rotor of both turbines was made from a thick iron rod which is 3.2 m long, 4.0 cm in diameter and was connected to two ball bearings which were placed at the opposite ends of the rod.

3.3.3.2 The Shaft

The shaft of both turbines was from a 2.9 m long and 5.0 cm in diameter iron pipe, strong enough to hold the blades. The rotor was placed inside the shaft and holes were drilled through the shaft in order to knot the shaft and the rotor together to enable the rotor to rotate as the shaft is rotating.

Ball Bearings

Two ball bearings each of diameter 5 cm were connected for both turbines. Their role is to hold the rotor firmly to the frame at both ends while transferring rotary motion of the blades. The ball bearings were properly greased to reduce friction and to ensure easy and higher rotational efficiency of the turbine

Mounting of both Turbines

The wind data used for the design analysis of both turbines were measured at a height of 10 m. it is necessary to have the wind turbines mounted at same height for optimal design performance. Therefore, a 10 m high rectangular stand was constructed using a 2-inch angle iron for each of the turbines; it was well braced to ensure that it can stand the weight of the turbine and speed of the wind from any direction to avoid vibration and noise from the turbine. A concrete base was constructed to hold the stand firmly to the ground and enough to stand the wind resistance at any wind speed in the study area.

RESULTS AND ANALYSIS

In order to test the performance of the mounted rotors, they were set into operation and monitored under the influence of same wind speed pattern that was used for the preliminary studies. Monitoring of both rotors were done simultaneously with the aid of a thermo anemometer and a tachometer. The thermo anemometer was used to measure the prevailing wind speed and the tachometer was well positioned to measure the Revolution Per Minute (RPM) of the rotors.

Savonius Rotor Analysis

The RPM of the savonius wind rotor at twenty one prevailing wind speed were recorded and plotted in Figure 3.

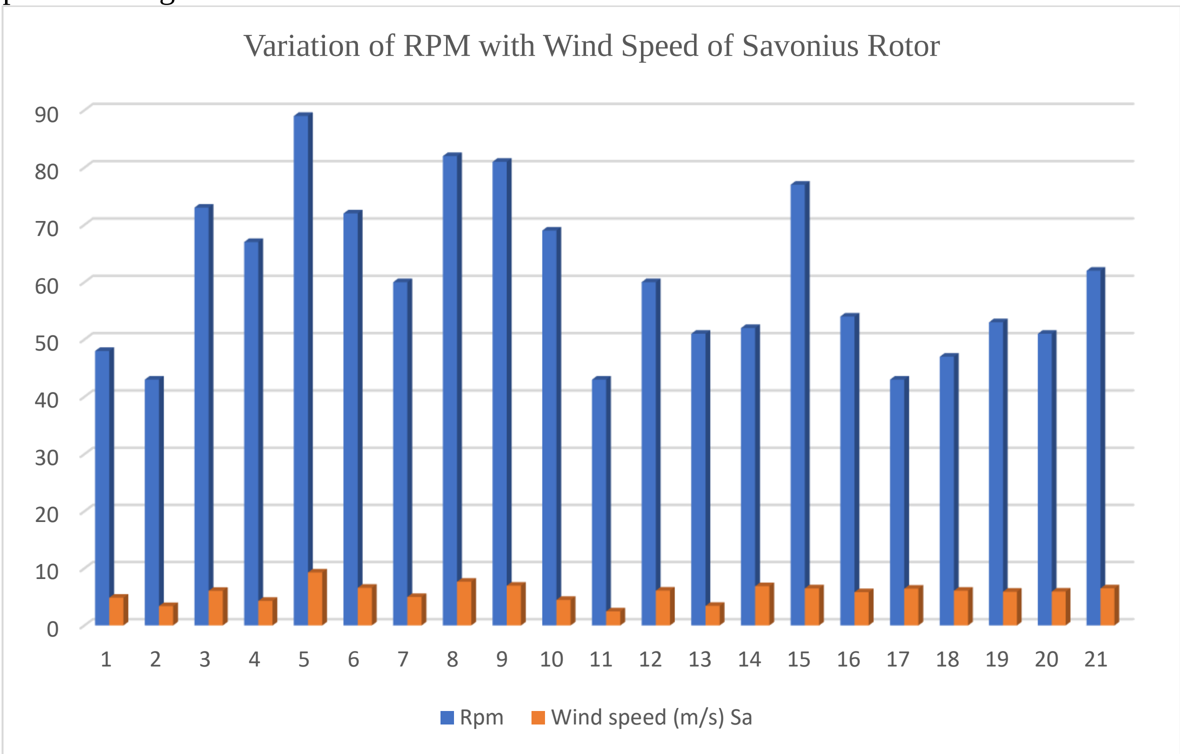


Figure 3: Variation of RPM and Wind Speed of the Savonius Rotor

From Figure 3, it shows that, the highest rotational speed per minute of the Savonius rotor was 89 at a wind speed of 9.28 ms^{-1} and the lowest of 43 RPM at a wind speed of 2.46 ms^{-1}.

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Darrieus Rotor Analysis

Similarly, the RPM of the Darrieus wind rotor at same wind speed recorded for the savonius type were recorded and plotted as shown in Figure 4.

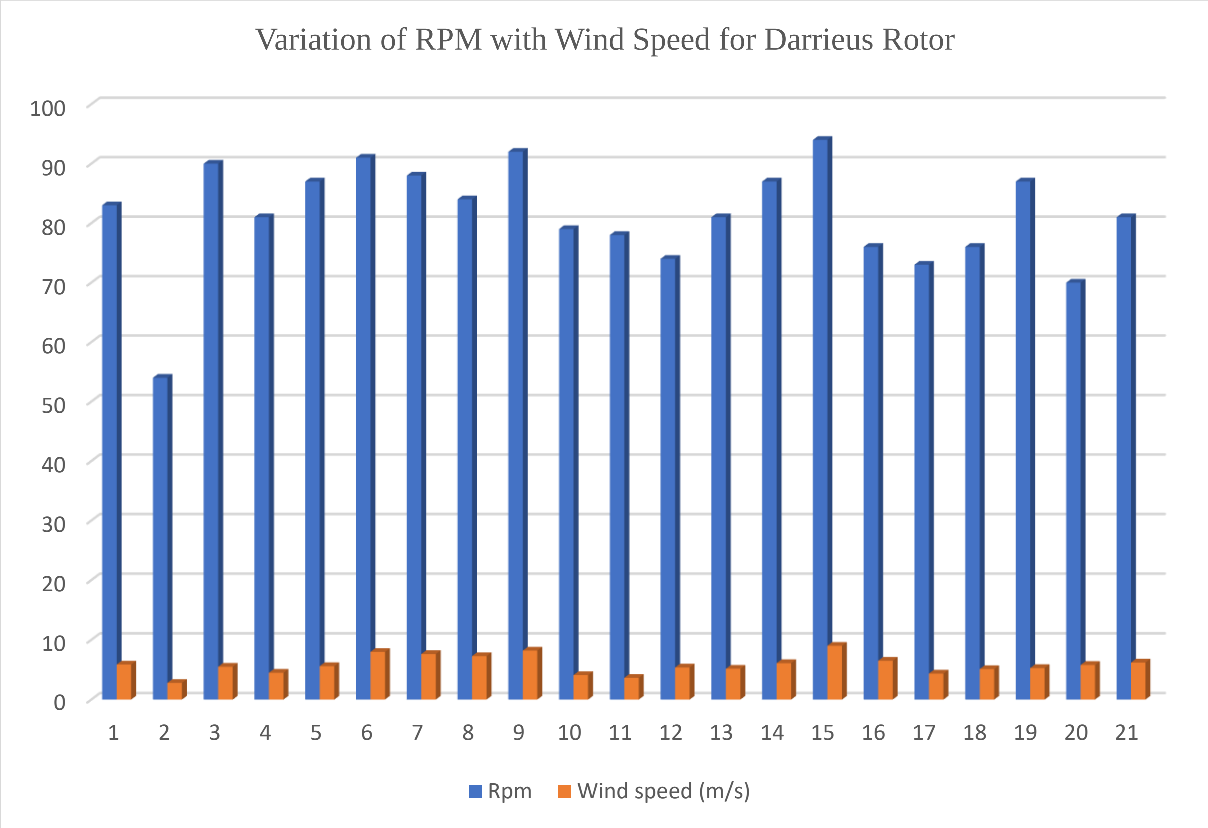

Figure 4: Variation of RPM with wind speed for the Darrieus Rotor

From Figure 4, it was observed that the RPM reached a maximum of 93 at a wind speed of 8.9 ms^{-1} and a minimum of 54 revolutions per minute at a wind speed of 3.8 ms^{-1}.

As part of the comparsm in the performance of both rotors, RPM values obtained for similar wind speed values were collected from Figure 3 and 4 and their average values were both worked out separately for both rotors. This resulted into ten sets of values of wind speed and RPM. The RPM values of both rotors were plotted together with their common wind speed values. Figure 5 shows the supposed effect of both rotors in a combined system in terms of wind speed and RPM values.

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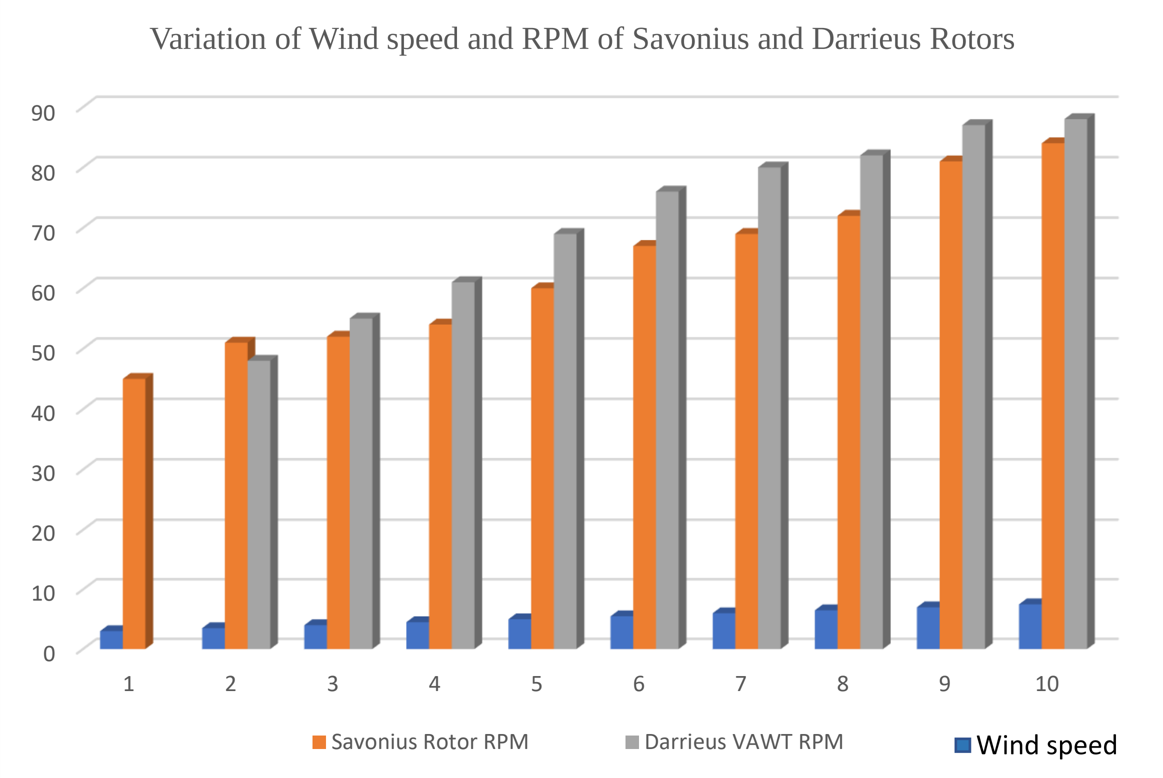

Figure 5: Comparing RPM of both Savonius and Darrieus Rotors

From Figure 5, it can be visually observed that for very low values of wind speed, the Darrieus wind rotor did not rotate. Only the savonius did rotate as seen with the first bar at a wind speed of 1.25 ms^{-1} and an RPM of 43.2. Subsequent increase in wind speed shows that the Darrieus type revolves more than the savonius beginning from bar 3 upwards as Darrieus takes the lead with longer bars. Of interest is the fact that, the Darrieus wind turbine did not pick up at a wind speed below 2.37 ms^{-1}. Below this wind speed value, the Savonius rotor performed better than the Darrieus as it will always respond to wind flow before the Darrieus VAWT. Both Darrieus and Savonius produced a maximum of 88 RPM and 84 RPM respectively when subjected to the same wind speed of 7.5 ms^{-1} as evident in the tenth bar. On the general, Darrieus wind rotor has a higher RPM than the Savonius wind rotor. That is, it performed better and has a higher rotational efficiency than the Savonius wind turbine.

It is clear that the performance of both rotors under same wind conditions are not the same. As expected, savonius has the advantage of self-starting at a lower wind speed while Darrieus has the advantage of high rotational speed after eventually starting. Both advantages can be optimized when both rotors are combined in a single system. Such combined savonous and darrieus wind turbine's performance can be obtained by combining the behavior of individual turbines in terms of RPM for a particular speed. For instance, for the second bar at a wind speed of 2.37 ms^{-1}, the Darrieus rotor picked-up with RPM of 47 which is lesser when compared to the savomious type with RPM of 50. For a combined system, both RPM's will sum-up to about 97. This combined rotational effect will result to a reinforcement of RPM for a particular wind speed.

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CONCLUSION

A standalone Darrieus VAWT and a standalone Savonous VAWT adaptable for the Usmanu Danfodio University community was constructed, field tested and compared in terms of their revolution per minute under same wind speed conditions. The results of this test showed that under the prevailing wind condition of the study area, the Savonius VAWT has a higher starting torque than the Darrieus VAWT but when the Darrieus blade starts it takes a longer time to stop, given its higher rotational speed reaching a maximum RPM of 93 and 89 to the Savonius at a wind speed of 9.28 ms^{-1} and 8.9 ms^{-1} respectively. This result is in agreement with Kragten (2004) and also buttress the need for additional research in the design characteristics of Darrieus VAWT in order to improve its superior capabilities in terms of starting torque. When values obtained for both rotors were combined into a single system, a combined rotational effect resulted. This implies reinforcement of RPM values for a particular wind speed. It was therefore recommended that a combined Darrieus and Savonius VAWT when constructed will optimize the high rotational efficiency of Darrieus and the high self-starting capabilities of savonius VAWT. Also, an appropriate generator having the bottom range of RPM specification less than the minimum measured RPM value of 43.2 should be used in order to increase the certainty of electrical output at all time. Such combined VAWT when intercepted by such appropriate generator will be competent to provide all-year-round electrical power to the host community.

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