255. Experimental Investigations of Hybrid Vertical Axis Wind Turbine

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Abstract

Horizontal axis wind turbines (HAWT) are considered to be more efficient than vertical axis wind turbines (VAWT); therefore, they have been the focus of current research studies. However, VAWTs have relatively lower cut-in speed in comparison to HAWTs and possess several advantages over HAWTs. If the efficiency of VAWTs can be improved, they may prove to be more suitable for urban areas where wind blows with low speed and have an irregular pattern. Darrieus and Savonius wind turbines are the most common VAWTs. The Savonius wind turbine is an aerodynamically drag based, self-starting turbine with low cut in speed but their inefficiency curtails them to fewer applications, whereas, Darrieus wind turbines are aerodynamically lift based turbines having higher cut in speed with higher coefficient of performance. This makes them unsuitable for sites with mediocre meteorological conditions. It has been experimented that by the combination of both Darrieus and Savonius rotor, higher coefficient of performance could be achieved at moderate wind speed. In present study, experimental investigations were carried out to explore the performance of hybrid Savonius and Darrieus wind turbines. A completely modular VAWT test setup consisting of a double staged Savonius and three bladed Darrieus turbine was fabricated to combine them into different arrangements; in order to conduct comparative studies. The experimental results showed that the combination of turbines in any arrangement resulted in an improved coefficient of performance and lower cut-in speed. The arrangement where Savonius rotor was placed at the middle of Darrieus rotor had a relatively higher coefficient of performance than other combinations studied in the previous work.

Keywords: Vertical axis wind turbine; Combined Savonius and Darrieus rotor; Coefficient of performance; Modular turbine system

1. Introduction

The rapid growth in world's population has placed great stress on the consumption of ubiquitous fossil fuels; as a result; these resources are being depleted in an accelerating manner. In the recent past, interest of the world has shifted towards clean and sustainable energy to overcome environmental issues associated with the use of fossil fuels and to curtail reliance on them in future. Renewable energy has become a relevant solution to the impending energy dilemma all across the world [1]. Solar and wind energies have been the fastest growing renewable energy sources since the 20th century. Wind Energy has contributed about 3.1% to world's electric demand from 2004 till 2014, which is the second highest contribution by any renewable energy resource [2]. Despite the endeavors borne by wind energy technologies to mature at western countries it has yet to gain recognition from the subcontinents, where lower wind velocity exists; especially in urban areas. The VAWTs have pivotal importance in such areas as they are low cut-in velocity wind machines; having moderate rotational speed with relatively lower noise levels [3]. There are two distinct types of vertical axis wind turbine: Savonius and Darrieus wind turbine.

1.1. Savonius Wind Turbine

The Savonius rotor was studied by many researchers since the 1920's and it was first introduced by a Finnish Engineer; Sigurd Johannes Savonius in 1931 [4].

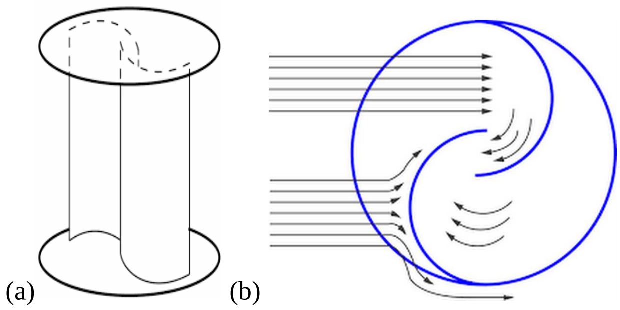

Fig. 1. Savonius wind turbine (a) typical Savonius rotor (b) working principle of Savonius rotor

The Fig 1(a) shows a typical Savonius wind rotor, which consists of two semi-cylindrical blades placed together in such a way that they form an S-shape, resulting in having two concave and two convex sides adjacently. Fig 1(b) illustrates the working principle of a Savonius rotor, when exposed to wind; a concave and an opposite convex sides of the rotor will always be facing the wind; this in turn creates a difference in drag forces exerted by the impinging wind on the curved blades, causing the rotor to rotate around its axis [5-6]. Savonius rotor generally has two blades; however, several experimental investigations have been carried out to analyze the performance of rotor with different number of blades. M. Hadi Ali (2013) conducted experiments for a Savonius rotor with two and three blades in order to investigate the effects of different number of blades on its performance. It was concluded that with the increase in number of blades; reverse torque increases as result net torque acting on the blades of rotor decreases. Therefore, Savonius wind turbine with two blades had higher power coefficient than three bladed Savonius wind turbine under similar test condition [7]. N.H. Mahmoud and A.A. El-Haroun investigated several parameters affecting the performance of Savonius rotor including: different number of blades, staging, end plates, aspect ratio as well as overlap ratio. It was found that the rotors with end plates had better aerodynamic performance than rotors without endplates also the efficiency improved with the increasing aspect ratio. Double stage rotors had higher performances than single stage rotors [8]. Fig 2 showcases the concept of overlap ratio in Savonius rotors.

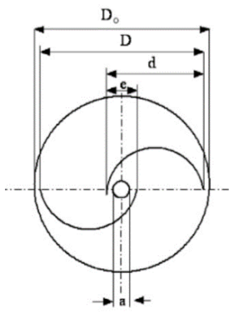

Fig. 2. Overlap ratio of a Savonius wind turbine

1.2. Darrieus Wind Turbine

Georges Jean Marie Darrieus, a French Engineer in 1931; invented the VAWT named Darrieus wind turbine. It was a US patent under the name “Turbine having its rotating shaft transverse to the flow of current” [9-10] consisting of two different configurations: Straight bladed type and Curved bladed type as illustrated in Fig 3a- 3b.

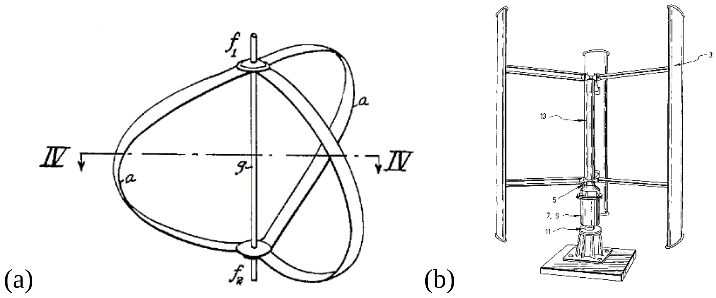

Fig. 3. Patented Darrieus rotors (a) Egg beater type (b) H-type

The turbines in Fig.3 (a) and (b) are generally known as Eggbeater type and H-type Darrieus, respectively. Eggbeater Darrieus type wind turbine has a troposkien shape. It possesses some advantages over H-type Darrieus. The curve shape minimizes the bending stresses experienced during centripetal acceleration while rotating; allowing for a better distribution of fluctuating aerodynamic loads [11]. Eggbeater Darrieus is also associated with various disadvantages including; complex and expensive blade design as well as vulnerable to dynamic stalling. Dynamic stall effect on the aerodynamic performance of the VAWTs blade was studied by Scheurich F *el at.* [12]. It was concluded from the study that straight blades have uniform local angle of attack distribution throughout the blade's span in contrast to curved blades and is easier to construct. A typical straight-bladed Darrieus wind turbine consists of 3-4 straight blades; connected to either a main link from center or supported by two main links at the top and bottom as showcased in Fig 4a and 4b.

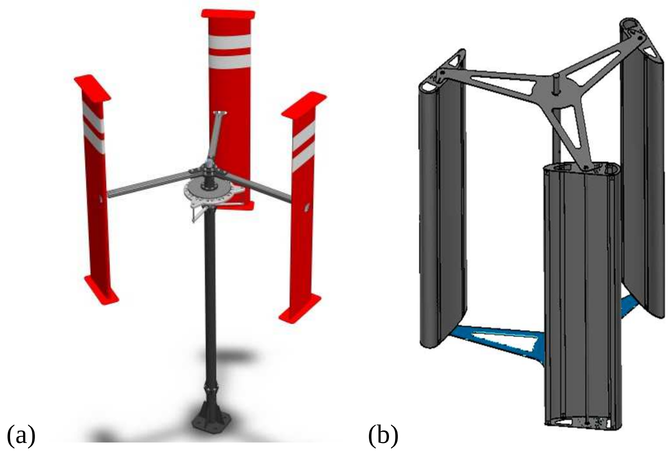

Fig. 4. Straight bladed Darrieus (a) main link at the middle of blades (b) main links at the ends of rotor

The Darrieus rotors are aerodynamically lift based devices, thus can rotate faster than the wind. These devices are used for power generation due to their high RPM rating, however they are not self-starting and have lower starting torque as well as dynamic stalling makes them less reliable in areas with weak prevailing wind.

1.3. Combined Savonius and Darrieus Wind Turbine

In present work, after reviewing the existing literature review, a three straight bladed Darrieus rotor; 0.54m in diameter and 0.66m tall was fabricated along with a double stage Savonius rotor; with diameter of 0.3m, an overlap ratio of 0.01m and height of 0.45m as illustrated in Fig 5a and 5b. They were combined together as depicted in Fig 5c, in order to overcome their demerits; the inability of Darrieus rotor to self-start and low starting torque will be corrected by attaching a Savonius rotor with it, which in-contrast has a high starting torque but lower efficiency [13-15].

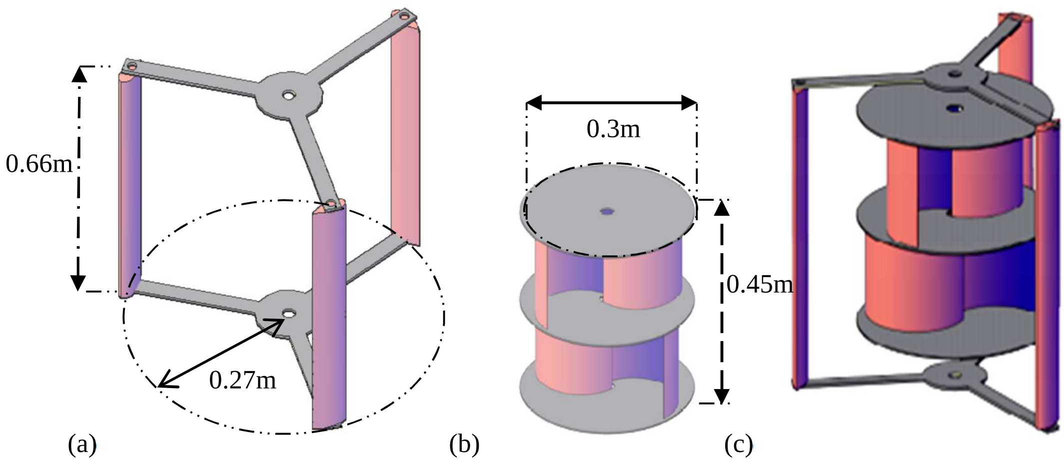

Fig. 5. Savonius and Darrieus rotor (a) Darrieus rotor (b) Savonius rotor (c) combined Savonius and Darrieus rotor

2. Experimental Test Setup

In order to evaluate the performance of the rotors individually and in combinations, a modular test setup was developed with detachable components as illustrated in Fig 6a. The setup houses three different shafts: central shaft, frame shaft and base structure shaft. The shafts can be made to act as a single unit by coupling them together with the help of fixed flange type couplings. The turbine base frame had steps for better structural support as well as to encompass equipment required for power transmission and generation. A pulley based transmission unit and a DC-motor acting as a generating unit is used in test setup. The central shaft hubs the rotor assembly; it can be detached from the system to change the configuration of the rotor assembly.

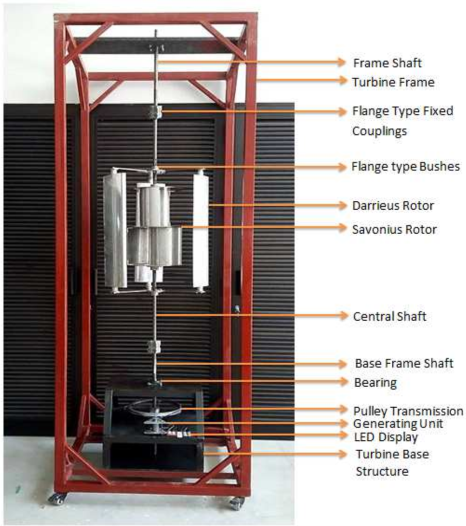

Fig. 6. Combined Savonius and Darrieus wind turbine (a) labelled setup A; Savonius at the middle of Darrieus turbine

Three different combinations of Savonius and Darrieus wind turbines are illustrated in Fig 6, 7a and 7b were referred as setup A, B, C. Setup A: Savonius placed in the middle of the Darrieus turbine as shown in Fig 6. The Fig 7a shows the arrangement used for setup B, in this arrangement Darrieus was placed above Savonius turbine. Configuration used for setup C is illustrated in Fig 7b, where Savonius was placed on the top of Darrieus turbine.

(a) (b)

Fig. 7 Combined Savonius and Darrieus wind turbine (a) Setup A; Darrieus at the top of Savonius turbine (b) Setup B; Savonius at the top of Darrieus turbine

3. Results and Discussion

Initially experiments were conducted for Savonius and Darrieus separately and the two turbines were combined together as explained in the section 2. In all five arrangements, experiments were conducted at various wind speeds varying from 1.5m/s to 5 m/s. In each case, the net power of the system was measured in terms of voltage and current, the rotor's RPM was recorded with tachometer. The experimental results obtained are discussed in this section. The values of parameter recorded at each speed were repeated four times and then were averaged to get the representative values. The coefficient of performance, extracted mechanical power and angular acceleration were calculated by using following set of equations provided as Eq. (1-3)

$$C_p = P_m \ / P_e \quad (1)$$

$$P_m = {}^{1}\!/_{4}\, \rho A (V_1 + V_2) (V_1 - V_2)^2 \quad (2)$$

$$\alpha = d\omega \ / \ dt \quad (3)$$

The plotted graphs of the average values for each wind rotors are illustrated in Fig 8-10. Experimental comparative study of the electrical power against different wind speed is presented in Fig 11. It can be observed that the setup A; Savonius at the middle of Darrieus rotor generated more power in contrast to Darrieus and Savonius rotors, individually. Furthermore, an average increment of 150% electrical power generated by the hybrid system over power generated by Savonius and an average of 22% over Darrieus turbine was noticed at all wind speeds in which the experiments were conducted.

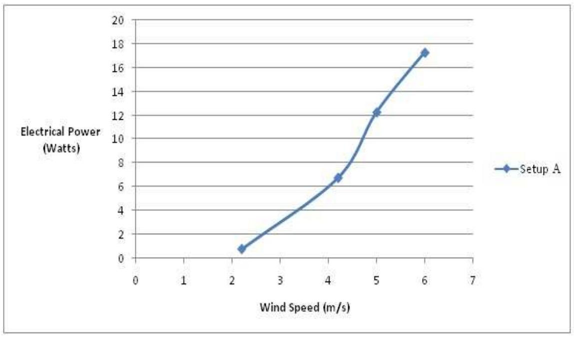

Fig. 8. Wind speed vs. Electric power: Darrieus rotor

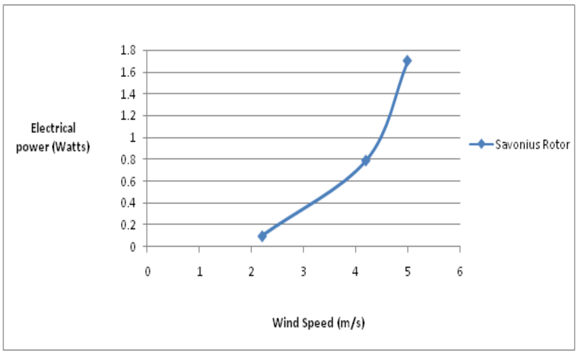

Fig. 9. Wind speed vs. Electric power: Savonius rotor

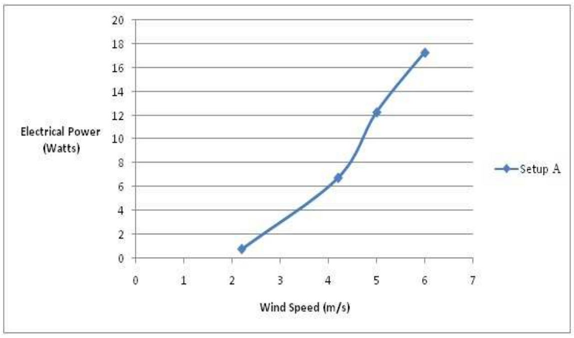

Fig. 10. Wind speed vs. Electric power: Setup A; Savonius at the middle of the Darrieus

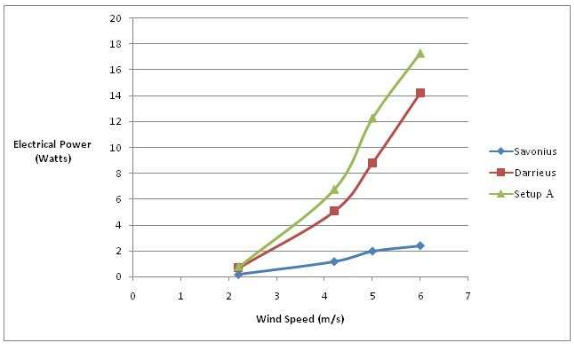

Fig. 11. Wind speed vs. Electric power: comparison between Savonius, Darrieus and Setup A

The combined setups A and B; could not be compared with the other rotors in terms of power generation as they had different swept areas than them, therefore, they were compared together on the basis of angular acceleration. The difference between them was that they had a different angular acceleration than each other. The Setup B; Darrieus on the top of Savonius rotor had a better angular acceleration than Setup C; Savonius at the top of Darrieus rotor. The comparison is depicted in Fig. 12.

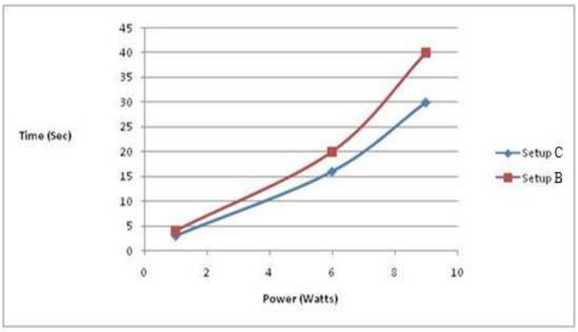

Fig. 12. Power vs. Time: comparison between Setup B and Setup C

The coefficient of performance of all the rotors was compared and is presented in Fig. 13. It can be seen that setup A, in which, Savonius rotor is placed at the middle of Darrieus rotor had the highest coefficient of performance

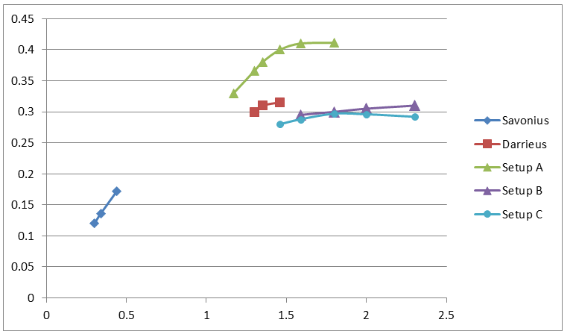

Fig. 13. TSR vs. Coefficient of performance

4. Conclusion

An experimental facility developed to conduct experimental study and analysis of wind turbine was fabricated and operated satisfactorily. The setup has provision to test vertical axis wind turbines. Hybrid VAWT was tested in three different configurations, namely; setup A, B, C. In setup A: Savonius was placed in the middle of the Darrieus rotor, in setup B: Darrieus rotor was placed above the Savonius rotor while in setup C: Savonius was placed at the top of Darrieus rotor. The Hybrid system showed better results than individual Savonius or Darrieus turbines in all cases studied in present work. It was also noted that Setup A produced better results than other combinations.

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Nomenclature

VAWT	Vertical Axis Wind Turbine
HAWT	Horizontal Axis Wind Turbine
C_p	Coefficient of Performance
P_m	Mechanical Power
P_e	Electrical Power
ρ	Density of Air
A	Swept Area of the Turbine
V_1	Wind Velocity before Crossing Wind Turbine
V_2	Wind Velocity after Crossing Wind Turbine
α	Angular Acceleration
$d\omega$	Change in Angular Velocity
dt	Change in Time