Common Vertical Axis Savonius-Darrieus Wind Turbines for Low Wind Speed Highway Applications

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Abstract-Wind energy is considered to be the fastest growing alternative of fossil fuel and a clean energy source. In this research work a combination of common vertical axis wind turbine is designed and tested specifically for the sites having low wind speed availability. This combination of Savonius and Darrieus rotor blades on a common shaft provides the benefits of both the starting at very low wind speeds and good efficiency. This combination has been used to recapture the wind power available on the highways due to the movement of the vehicles. Savonius rotor blades being self-starting at low wind speeds help the Darrieus rotor blades to rotate which have greater efficiency than Savonius. Average wind speed available at the highway during this study is taken to be 4.8 m/s. Up to 37% efficiency is achieved by using this combination at a tip speed ratio of 0.9 and with no overlap conditions. With the increase in tip speed ratio, the overall efficiency and power coefficient increases. At high wind speeds, the tip speed ratio and power coefficient decreases.

Index Terms—wind energy; Savonius; Darrieus; self-starting; tip speed ratio; power coefficient

NOMENCLATURE

Abbreviations

VAWT	Vertical Axis Wind Turbine
HAWT	Horizontal Axis Wind Turbine
FOWTs	Floating Offshore Wind Turbines
TSR	Tip Speed Ratio
NWT	Numerical Wind Tunnel
CFD	Computational Fluid Dynamics
RPM	Revolutions per Minute

List of Symbols

D	diameter of Savonius rotor blade
H	height of Savonius rotor blade
R	radius of Darrieus rotor blade
L	length of Darrieus rotor blade
A_s	swept area of Savonius rotor blade
A_{sd}	swept area of Darrieus rotor blade
ω	angular speed of the rotor
λ	blade tip speed ratio
V_b	blade tip speed
V_a	average ambient wind speed
P_{th}	theoretical power to drive the turbine
P_{act}	actual available power
η_{th}	theoretical efficiency
η_{act}	actual efficiency
T	actual torque
T_w	theoretical torque
I	current
V	voltage
A	total swept area
ρ	density of the air
P	turbine output power/ shaft power
C_P	power coefficient

I. INTRODUCTION

Wind energy being environmental friendly and abundantly available in the earth's atmosphere is considered as a potential alternative source of fossil fuels. Dependency on fossil fuels can be reduced by the help of such a potential alternative energy source and its importance is being recognized in many developing countries.

A well designed wind rotor machine like vertical axis wind turbine can help to meet the desired power by utilizing the available wind energy to its maximum. Generally horizontal axis wind turbines (HAWT) are considered as more suitable in terms of their efficiency as compare to vertical axis wind turbines (VAWT) but later ones are considered to be more advantageous in terms of safety, compact design, cost and operation in urban environments. Moreover even at low blade speed ratios and with zero net mas flux actuation, better robust power output can be achieved [i]. Common VAWTs are shown in Fig. 1.

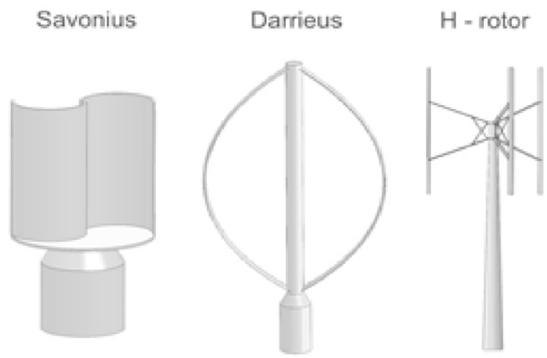

Fig. Common VAWTs

VAWTs can be easily installed on building rooftops and areas of turbulent flow with more success than HAWTs and thus find wide use in domestic, private and commercial applications where turbine placement and wake effects are the major concern [ii]. VAWTs are well suited for offshore wind energy exploitation as floating offshore wind turbines (FOWTs) using suitable mooring line models [iii]. A more suitable hydrodynamic model for floating offshore wind turbines is Cummins equation with number of modifications. Moreover fixed support structures are not technically suited for offshore wind applications so floating support structures are necessary for deep offshore wind turbines to become economically viable [iv]. Savonius rotor vertical axis wind turbine is a drag type VAWT, initially developed in late 1920s by dividing a cylinder into two equal semi-cylindrical surfaces and then moving them sideways along their cutting plane [v]. Savonius rotors with two blades, end plates and with no overlap give better performance [vi]. The aerodynamic noise of Savonius rotor can be predicted by applying FW-H equation. S-shaped Savonius turbine with a twist angle of 20^0 was found to provide the maximum reduction in the noise [vii]. Creating wind jets towards the concave side of advance and return rotors of Savonius turbine rotor can significantly enhance its performance, however the wide wake produced around and behind the rotors must be considered [viii]. Bronzinus is a novel type of VAWTs which gives better coefficient of performance as compare to the classical Savonius turbines [ix]. Darrieus wind turbine being a lift type of a VAWTs that was invented by a French inventor, George Darrieus, having two or three curved shaped blades with airfoil type cross section having constant chord length [x]. Adaption of accurate blade Reynolds number (Re) in case of Darrieus wind turbine is necessary to predict correct information at high tip speed ratios [xi]. The most commonly used mathematical models for performance prediction of Darrieus turbine are: vortex model, cascade model, double multiple stream line model and blade element momentum (BEM) model [xii, xiii]. Increasing the tilt angle of Darrieus wind turbine causes reduction in power production and coefficient of performance and hence it must not exceed the angle at Troposkien root which is at 300 [xiv]. Improvement in power coefficient up to 51% had been observed in combined Darrieus-Savonius rotor with no overlap and reduction in power coefficient was observed with the increase in overlap [xv]. The main contribution of Savonius rotor in Darrieus-Savonius rotor is to provide the starting torque at different intensities and directions of inlet air [xvi]. The net power output of VAWT can be improved by properly positioning it behind the deflector plate [xvii]. Optimum hybrid H-Savonius rotor shows improved performance in terms of its self-starting ability at all azimuthal angles and better output as compare to other existing H-type vertical axis wind turbine rotors [xviii]. Numerical wind tunnel (NWT) technique is commonly used to study the performance of VAWTs by analyzing the flow around and inside the multistage VAWTs surrounded by stator vanes [xix]. Computational Fluid Dynamics (CFD) gives a good insight to study the aerodynamics of VAWTs as compare to computational aerodynamics and can analyze the flow patterns around the airfoils [xx].

In this experimental work, a combination of combined vertical axis Savonius-Darrieus rotor wind turbine is proposed and successfully implemented for extracting the wind energy available from the high speed moving vehicles on the highways. The wind turbines are designed to be placed in high traffic areas on the medians to utilize the maximum amount of available wind energy and hence fluid flow from both sides of the highway is considered in this design. Up to 37% efficiency has been achieved by the proposed setup.

II. DESIGN OF SAVONIUS-DARRIEUS WIND TURBINE

In present experimental work a hybrid Savonius-Darrieus rotor VAWT is designed and tested for highway applications with both turbines on the same common shaft. Savonius rotor being self-starting but less efficient at low wind speeds is used to start straight bladed Darrieus rotor which has greater efficiency than Savonius [xxi]. The aim is to combine both types of turbines to increase overall efficiency of the system and to convert maximum available wind energy into useful work with less complexity in design and cost effectiveness.

A. Blades

The blades designed for Savonius-Darrieus rotor in this study are of aluminum alloy, Al-2024 due to its light weight, low cost and good mechanical properties.

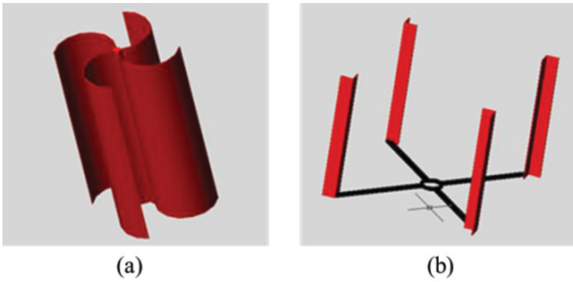

Fig. 2: (a) Savonius rotor blades (b) straight bladed Darrieus rotor blades

Number of blades selected during the current study are 4 as they produce more torque than 3 blades at low TSR [xxi] and at an angle of 90^0 to each other as shown in Fig. 2.

These blades are obtained by bending and rolling aluminum sheets having a height of 2 feet and 1mm thickness as shown in Fig. 3. The zero overlap condition has been used.

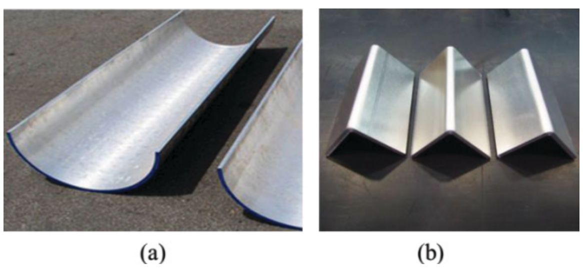

Fig.3: (a) Savonius rotor blades (b) Darrieus rotor blades

Properly fitted hollow aluminum shaft having diameter of 1 inch and total length of 3.5 feet is used to transfer rotational energy obtained from hybrid Savonius-Darrieus rotor blades to the generator. Partition plates made of aluminum are used between the Savonius-Darrieus rotors and cast iron flanges are used to attach spoke arms to the shaft. Complete 3D model of hybrid Savonius-Darrieus rotor VAWT is shown in Fig. 4.

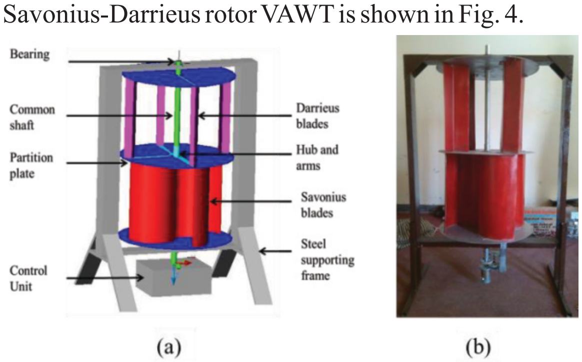

Fig. 4: (a) 3D model of Hybrid Savonius-Darrieus rotor VAWT (b) fabricated model

Control units consisted of gear box having gear ratio of 1:13 to increase the available rpm, ammeter, voltmeter, DC to AC converter, fuse and battery for power storage. VAWT has a rectangular shaped swept area given by (1) & (2) for Savonius and Darrieus rotors respectively [xxii]:

$$A_s = \pi \times D \times H \quad (1)$$

$$A_{sd} = 2 \times R \times L \quad (2)$$

Swept area limits the volume of the air passing by the turbine and power output directly depends upon the swept area. Total swept area in this study is 0.8 m2. For stability the diameter to height ratio (D/H) is kept to 1.2.

Different designs are being proposed by different researchers [viii] to utilize the input power of the wind to its maximum. Wind diverter is one of the techniques that can be applied to get maximum power from the wind available by converging it towards the turbine rotor as shown in Fig. 5.

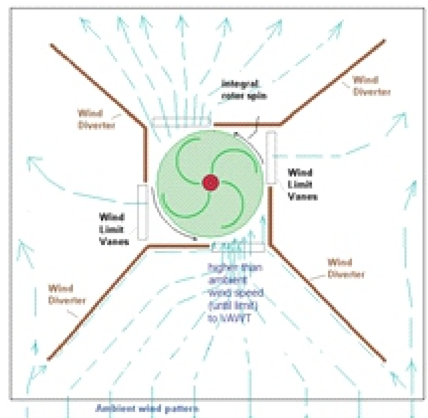

Fig. 5: Wind diverters to increase the input wind power

The function of wind diverters is to harvest the wind power by converging it to high velocity jet which strikes on the concave side of Savonius blade and a guide mechanism designed to limit the wind flow on convex side. Hence it helps to increase the positive torque and reduction in drag. Several configurations have been investigated for obtaining maximum torque and reducing drag.

A. Tip Speed Ratio (TSR)

The power coefficient depends upon the blade tip speed ratio (λ) which is the ratio of blade tip speed (Vb) and average wind speed (Va) available, in our case it is 0.99 and average available wind speed measured by anemometer is 4.8 m/s. The number of revolutions as measured by tachometer is 180.

$$\lambda = \frac{V_b}{V_a} \quad (3)$$

where,

$$V_b = \omega \times R$$

For different tip speed ratios, the theoretical efficiency for ideal VAWTs can be calculated using following relations as provided in Table I

TABLE: THEORETICAL EFFICIENCY RELATIONS FOR IDEAL VAWT [xxii]

1	For $0.5 \leq \lambda \geq 1$	η_{th}=0.196 × λ+0.23233
2	For $1 \leq \lambda \geq 1.5$	η_{th} =0.104 × λ+0.32433
3	For $1.5 \leq \lambda \geq 2.5$	η_{th}=0.055 × λ+0.399
4	For $2.5 \leq \lambda \geq 4$	η_{th}=0.022 × λ+0.481
5	For $\lambda \geq 4$	η_{th}= 0.078369×λ^2 + 0.92146 × λ

Power and efficiency of the VAWTs can be calculated by the following equations [xxi, xxiii,xxv]:

$$P_{th} = \frac{1}{2} \times \rho \times A \times V_{a^3} \quad (4)$$

$$P_{act} = I \times V \quad (5)$$

$$\eta_{th} = \frac{2\times T\times \omega}{\rho \times {V_a}^3 \times A} \quad (6)$$

$$\eta_{act} = \frac{Output}{Input} \quad (7)$$

$$P = P_{th} \times \eta_{th} \quad (8)$$

Efficiency of conversion of available energy can be represented by power coefficient (Cp) which is the ratio of turbine output power to the power of wind [xxi, xxiv] as in (9):

$$C_p = \frac{P}{P_{th}} \quad (9)$$

Whereas, coefficient of torque (C_t) is given by (10):

$$C_t = \frac{T}{T_w} = \frac{4T}{\rho\, A_s\, d\, {V_a}^2} \quad (10)$$

III. Results And Discussion

The hybrid Savonius-Darrieus rotor VAWT is designed for highway applications. The average speed of air available at the installation site from the movement of vehicles as measured by anemometer is 4.8 m/s. It can vary depending upon the traffic, vehicle speed and weather conditions. This design of combining the Savonius and Darrieus rotor on a common shaft helps to increase the overall efficiency of the system and wind energy from the both sides of moving vehicles is used as input which helps the turbine rotors to rotate smoothly and speedily. The wind power available to a single unit to drive the turbine, refer to (4) is 54.6 watt and hence the theoretical efficiency for an ideal VAWT with tip speed ratio of 0.9 is 42%,refer to (6). Theoretical power output is 23 watt calculated as in (8).

A number of such units can be installed on the highways which are grid connected to obtain maximum power from this clean alternative energy source and this addition is quite useful in meeting the fastest growing electricity demand.

Numerical simulation using standard finite element software is an important tool applied nowadays [xxvi, xxvii]. Numerical simulation using ANSYS resulted that the turbine with 4 blades produces more torque at low TSR while turbine with 3 blades show optimum performance at TSR [xxi].

The actual power output of turbine has been compared with the theoretical power output at various wind powers in the Fig.6. With the increase in tip speed ratio,both actual as well as theoretical powers are reduced.

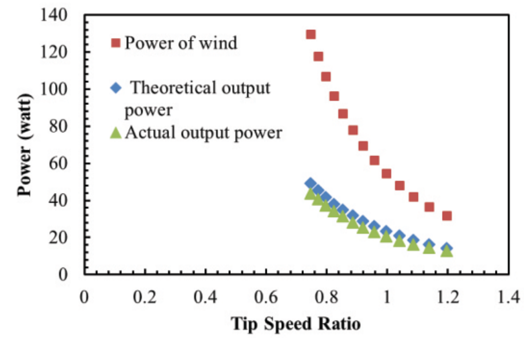

Fig. 6: Actual and theoretical power outputs at various TSRs and available wind powers

TSR is found to have an inverse relation wind speeds as shown in Fig. 7. On the other hand TSR is found to have a direct relation with the overall efficiency as shown in Fig. 8.

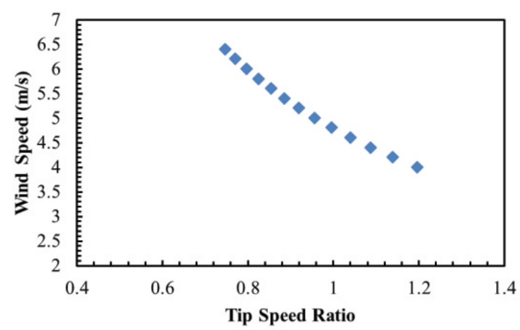

Fig. 7: Variation in TSR at various wind speeds

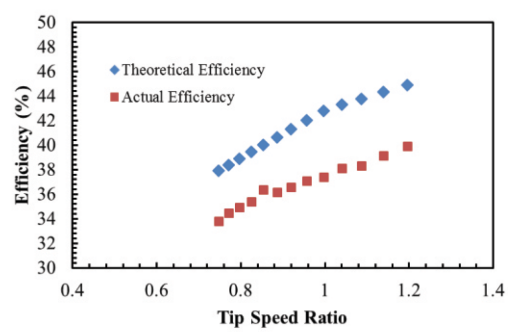

Fig. 8: Increase in efficiency with increase in TSR

Also it is found that with the increase in tip speed ratio the power coefficient increases while it has an inverse relation with the wind speed as shown in Fig. 9.

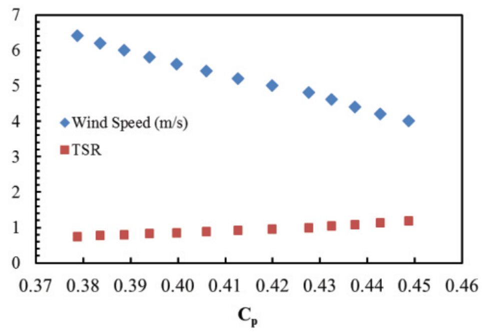

Fig. 9: Change in power coefficient at various wind speeds and TSR

The actual power output available as calculated by using (5) at the average wind speed of 4.8 m/s is 20.4 watt and the actual efficiency achieved is 37% which is very acceptable in comparison with the theoretical efficiency of 42% considering several factors like weight of the assembly etc.

IV. CONCLUSIONS

The proposed design of hybrid Savonius-Darrieus turbines for highway applications is very useful as an alternative energy resource. Installing a number of such units increase the overall power output thus utilizing the maximum amount of available wind energy. The average available wind speed during the current study is 4.8 m/s and the hybrid configuration of Savonius-Darrieus VAWT has an efficiency of 37%. Up to 20 watt power output is obtained. Also with the increase in TSR, the overall efficiency and power coefficient increase. At high wind speeds, the TSR and power coefficient decreases.

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