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HYBRID KINETIC TURBINE ROTORS: A REVIEW

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Abstract

A kinetic turbine rotor is a primary component of the kinetic energy system. The rotor design is very tedious jobs to achieve Betz's efficiency limit. Many rotors with good efficiency suffer lesser starting torque or drag problems leading to starting issues. Through the literature hereby revised, it is seen that, to compensate the disadvantage of one with advantage from another rotor, many attempts have been made to design hybrid rotor of the wind turbines. A simple hybrid turbine offers two rotors on the same shaft of the wind turbine which can be vertical or horizontal. It can harness kinetic energy from wind, river stream, or others fluid streams. In this paper, various approaches of hybrid kinetic turbine rotor have been described and their applications and a typical comparison has also been carried out. The current work helps identify the hybrid kinetic turbine an efficient option against any/most single rotor kinetic turbine.

Index Terms: *Wind turbine, hybrid rotor, VAWT, HAWT.*

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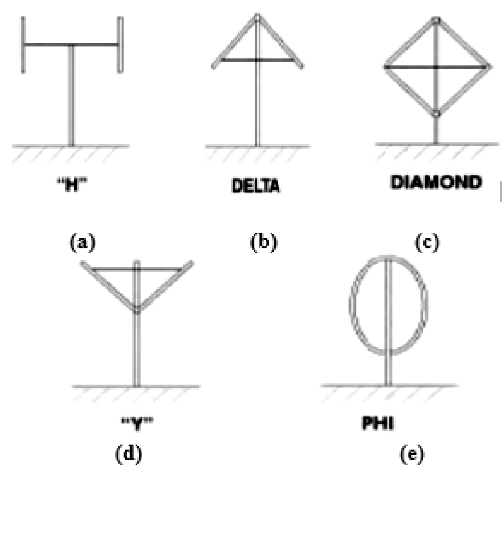
1. INTRODUCTION

Electrical energy is the form of energy having the highest demand from remote to convenient locations for connections from power grids, from daily needs of a household to prime movers requirement in any industry. World total domestic electricity consumption in 2012 was 195000 TWh and 804 TWh in India [1].The peak power deficit has been reached up to 11.4% in India [2].There has been a deficit of electrical energy and its generation is hoped not to contribute to ever critical environmental issues and thus find opportunities to replace fossil fuels by renewable counterparts. To meet this energy requirement, 20% renewable power generation has been contributed in 2012 and 13.6 % in India [3]. Simplest of renewable energy source with a history of dedicated effort towards development is the kinetic energy available through natural water streams and wind throughout the globe.

1.1 Kinetic Turbine Rotors

As we know, the kinetic turbine works on the Bet'z momentum theory principle. The kinetic turbine may be used for wind or water both having same power generation concept. Design of kinetic turbine rotor is influence by the density of the flowing fluid therefore the size of the hydrokinetic turbine rotor is smaller. Especially, Water turbine rotor should be strong enough to sustain the high-speed energy flow, rather than wind turbine rotor.

Though, the configurations of turbine rotors are same. Many configurations of wind turbine rotor are shown in Fig. 1 and 2. Vertical axis rotors are oldest type wind turbine rotors. Savonius rotor and H- type rotors could only be built as pure drag type rotors. It was only recently that engineers succeeded



ISSN: 2250-3676
Volume-4, Issue-6, 453-463

Fig- 1: Vertical axis wind turbine's rotor configurations [4]

in developing vertical axis "Darrieus" type rotor, which could also effectively utilize aerodynamic lift. Energy converters, which have their axis of rotation in a horizontal position, are realized almost based on "propeller-type" concept. .

Wind turbine rotors mainly are two type HAWT rotors and VAWT rotors. Mostly H-type, Darrieus and Savonius type rotors are used as vertical configuration. However, eggbeater turbine rotors are used at times in which lift force is utilized. On Other hand in rotors with horizontal orientation two blades or three blades rotor turbine are in use as an efficient rotor HAWT or A hybrid rotor is made by combination of two VAWT's rotors.

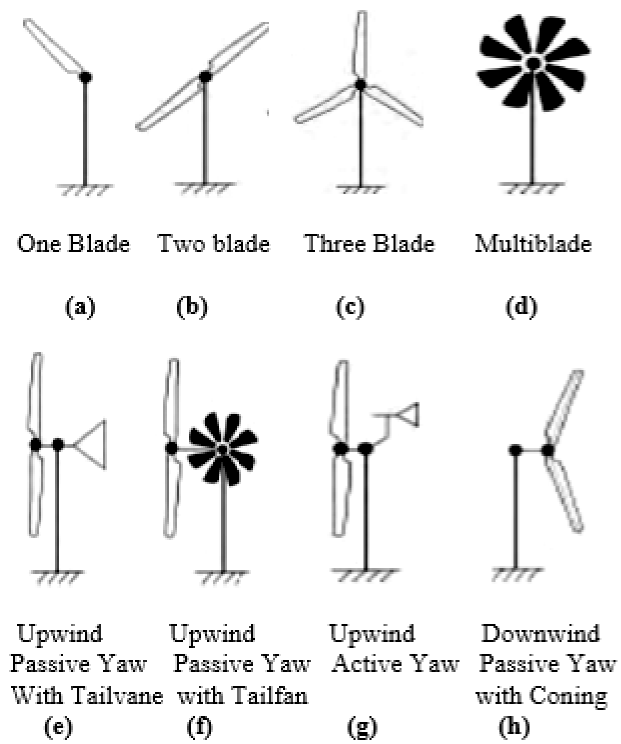


Fig- 2: Horizontal axis wind turbine's rotor conFigurations (a) One Blade (b) Two blade (c) Three Blade (d) Multi-blade (e) Upwind Passive yaw with tail vane (f) Upwind Passive yaw with tail fan (g) Upwind active yaw (h) Downwind passive yaw with coning

2. TYPES OF ROTORS

Two of the basic rotor types of wind turbine have been described in following subsections which are used in hybrid turbine configuration

2.1 Savonius Rotor

The Savonius turbine is designed by cutting a Flettner cylinder into two splits along the central plane and then moving the two semi-cylindrical surfaces sideways along the cutting plane so that the cross-section resembles the letter 'S'[5]. Savonius turbine has high starting torque and its coefficient of power (Cp) generally varies between 15- 35 % [6]. According to the Ghosh et al. single rotor configuration has maximum power power coefficient of 19 % at a Reynolds number of 120,000 and also estimated discharge for single stage turbine rotor of 3 m diameter at design speed of 6and 8.5 m/sec were 5,000 and 6,000 m^3 /month to be used for roto-dynamic pump.

The flow energy utilization of Savonius rotor is 20% [7]. Thus, this type of turbine is generally not used for high-power applications but for wind velocimetry applications [8]. This turbine basically uses drag force of wind thus its self-start advantage makes it different from other lift force based wind rotors.

2.2Darrieus Rotor

Darrieus wind turbine rotors are lift based devices; it was first presented by G.J Darrieus, a French Engineer in 1925. Darrieus wind rotor has two or three thin curved blades with aerofoil cross section profile and constant chord length [9]. A Darrieus rotor has varying angle of attack in a revolution between -20° to +20°, since at higher angles the flow along the blade is no longer laminar [10]. Darrieus type wind rotor has many variants, all of which use lift force to cause the rotor to rotate and hence generate electricity [11]. Various Darrieus type wind turbine rotor configuration given in table 1.

Table 1 Darrieus type rotors [11].

Darrieus rotor configuration	Maximum capacity
Egg beater type	4 MW
Straight blade type	10 kW
Variable geometry oval trajectory	Prototype Only
Masgrowe type	3 kW
Twisted three bladed rotor	Prototype Only

ISSN: 2250-3676
Volume-4, Issue-6, 453-463

These machines take advantage of the lift generated by the aerofoils moving through the water or wind. Alam et al. [12] carried out the Darrieus rotor design in which the aerofoils used are symmetrical and have a zero pitch angle. Darrieus turbine has versatile feature for the application of wind or water. Thus it can be used as a combination for the hybrid wind rotors.

3. HYBRID ROTORS

Hybrid rotors are the combination of two different rotors mounted on the same shaft. Mostly hybrid wind or water rotors are available in the vertical axis configuration. Hybrid rotors generally combine Darrieus and Savonius type wind rotors. However, many other configurations might be available for designing of hybrid rotors. A hybrid turbine overcomes the shortcomings of the one fold aerofoil turbine rotors and takes advantage of another turbine rotor. Many attempts have been made to design hybrid kinetic energy rotors, which have been described in following sections.

4. CONFIGURATIONS

4.1 CT-SBVAWT (Combined Type Straight-Bladed Vertical Axis Wind Turbine)

This type of rotor configuration has three parts upper Savonius blade, lower Darrieus blade and overrunning clutch. S- Blade is fixed on the top of wind rotor. It consist two stages upper and lower, which are set at 90° to each other. H- Blade is the primarily body of the hybrid rotor, which existed under the S-Blade. Another device, clutch used as separator, exist between the two rotors. At high wind speed it separates the rotors. The clutch has mainly two functions: one is changing the speed. It ensures H-blade can rotate faster than S blade on the premise of an unbroken kinematic chain between S-blade and H-blade. The other is averting backspin. The one-way clutch transfers torque in a direction of rotation and run idle in the reverse direction. Figure 3.1 shows structure of the hybrid wind turbine rotor.

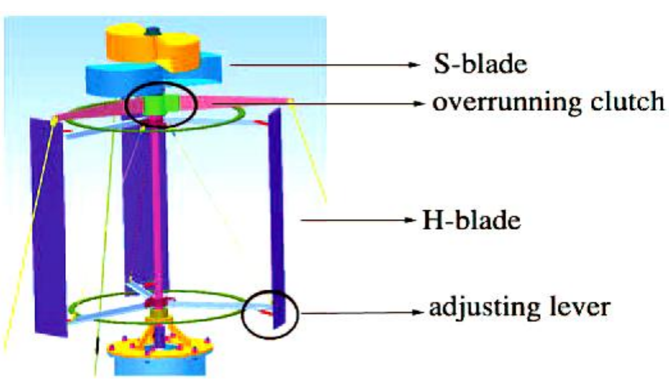


Fig- 3: Structure of the combined blade [13]

Kou et al. [10] determined that hybrid rotor configuration has a good starting characteristics and better energy utilization at higher flow speed. However, expected performance of the rotor has not been significantly achieved.

4.2 Eggbeater Darrieus

Savonius (Type A): Wakui T et al. [14] developed two types of configuration combined with eggbeater Darrieus and two stage Savonius. In case of Type A, Savonius rotor is mounted inside the rotational closed space of the Darrieus rotor, accentuating its compactness as a stand-alone power system. The design of the hybrid clearing becomes complicated though the output enhancement due to the hybrid clearing is insignificant because of having to set the radius ratio for both rotors such that the Savonius rotor takes the load to the Darrieus rotor at the maximum power coefficient point for the Darrieus rotor, and because of the Savonius rotor wake effects that naturally occur after hybrid clearing. Figure 4 shows design of the Type –A wind turbine rotor.

Type- A rotor has maximum power coefficient point Cp=0.204 at Tip speed ratio 3.51. In type A, the design of the hybrid rotor clearing becomes more complicated as the output enhancement and radius ratio of both rotors keep such that the Savonius rotor takes the load to the Darrieus rotor at the maximum power coefficient point for the Darrieus rotor.

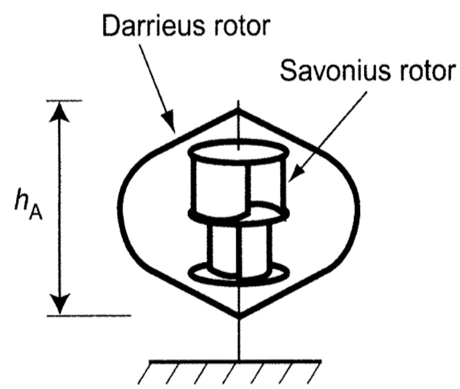


Fig- 4: General view of Type-A hybrid rotor configuration

Because of the Savonius rotor wake effects occurs after hybrid clearing. This configuration has burden of interference of wind than the single Darrieus rotor and it lead the lower power

ISSN: 2250-3676
Volume-4, Issue-6, 453-463

output. However, the power coefficient is improved in low TSR region.

Savonius (Type B): Comparatively, Type B hybrid rotor more suitable for high TSR ratio due to its high power coefficient 0.231 at TSR 3.76. The turbine is larger than the compact configuration of Type A shown in Fig 5. By evaluating the scale model behaviour of Type B hybrid rotor, the results are not good to perform in large scale system.

Wakui, E. et al. [14] suggested The Type-A configuration is more useful than Type-B due to it compactness and good electric power performance.

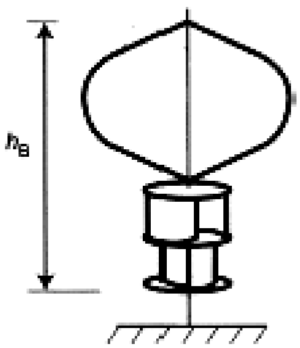


Fig- 5: General view of Type-B hybrid rotor configuration

4.3Three bucket Savonius and three-bladed Darrieus

A computational study of combined Savonius–Darrieus has been made by Gupta, R. et al. [6]. Overall aerodynamic lift of the Savonius turbine has been decreased and resulted decrease in velocity and pressure difference across the bucket having overlaps in blade. Close interaction of vortices occurs near the bucket region and it augmented the power for the combined configuration.

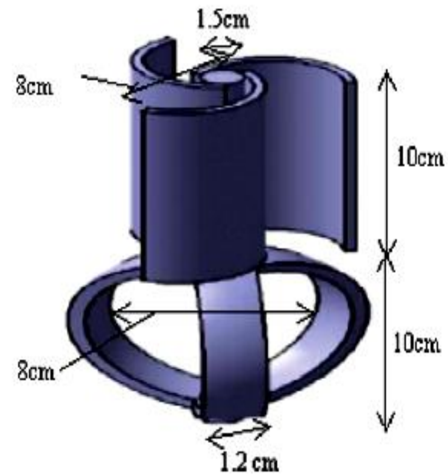


Fig- 6:Combined three-bucket-Savonius-three-bladed-Darrieus turbine.

A hybrid configuration and dimension of Savonius-Darrieus has shown in Fig 3.4. CFD analysis of this configuration has approved this configuration with experimental work by Debnath et al. [15].

4.4Two- Bladed Darrieus and Savonius rotor

(A) On a common rotor

Combined Darrieus –Savonius turbine has been proposed by Kyozuka, Y. et al [16] to improve the lower starting torque of Darrieus turbine. A top view of Hybrid turbine configuration has shown in Figure 3.5 which has two bladed Darrieus and two bucket Savonius. Different attachment angle between two rotors has been tested to improve the torque and power of assembly.

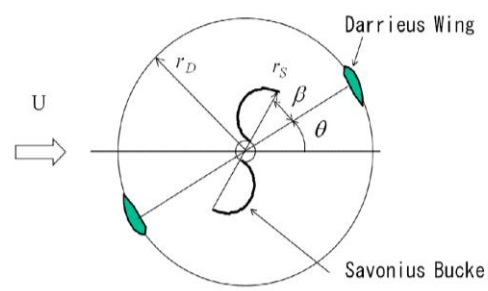


Fig- 7: Combined Darrieus wings and Savonius Bucket.

The power generation and overall performance of the hybrid rotor has been improved slightly. The starting torque of the rotor increased but the power coefficient and rotor torque was decreased by 70%, as compared to single Darrieus rotor. It

ISSN: 2250-3676
Volume-4, Issue-6, 453-463

was suggested that Darrieus–Savonius turbine should not make coaxially but should be independent in axial direction.

(B)With ratchet mechanism or one way clutch attached to the Savonius rotor

The power generation of the combined turbine was found to drop by 30% against the compensation of enhancement of starting torque. Thus, to improve the performance of the combined turbine, with an intuitive approach, the applicability of ratchet mechanism or one-way clutch on the Savonius rotor was tested [16]. Experimental results concluded that the torque of the combined turbines is smaller than solo Darrieus turbine. It was suggested that the degraded performance was the result of interference by the Savonius rotor blades to the Darrieus wings. Thus, a ratchet mechanism has not been a successful option.

4.5Straight blade Darrieus and Two stage Savonius Hybrid Rotor

An innovative Darrieus Savonius configuration has been adapted by Alam M.J. et al. [12] to design hybrid rotor for water current turbine. He used two stage Savonius rotor as a good start up device and four bladed Darrieus rotor as main device the pictorial view has shown in Fig 3.5.

They are combined perpetually to the same axis. To get good start-up features irrespective of the water direction, the Savonius rotor is divided into two (upper and lower) stages, with the two parts having an attachment angle separated by 90°. He found that cut in speed of the hybrid rotor is about 0.3 m/s and it results the quick stating torque in water application. In addition, the design of a hybrid turbine, it is recommend choosing a proper radius ratio of the turbines as well as proper positioning of two turbines.

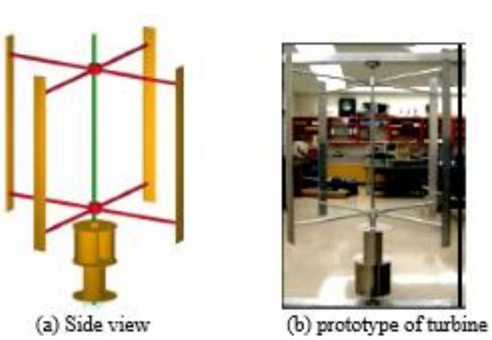


Fig- 8: Combined Savonius-Darrieus Water turbine

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4.6 ERIGEN combined Darrieus–Savonius Rotor

A hybrid turbine had used for telecommunication system in Sweden [17]. The hybrid turbine was designed by combining 3 bladed Straight Darrieus rotor and two stage Savonius rotor. Figure 3.6 show the ERIGEN turbine testing in high voltage laboratory.

The first hybrid ERIGEN turbine was installed at light house of Baltic south of Sweden in 1983. The turbine had generated 62 kWh in one year with solar power system. The report has concluded that the hybrid wind rotor is unique power generation device for remote locations. The aerodynamic torque utilized mainly three bladed Darrieus rotor. However, turbine is started by Savonius rotor at wind 3 m/s and Darrieus turbine starts to operate at about 4 m/s and stay operating down to approx. 3.5 m/s.

ISSN: 2250-3676
Volume-4, Issue-6, 453-463

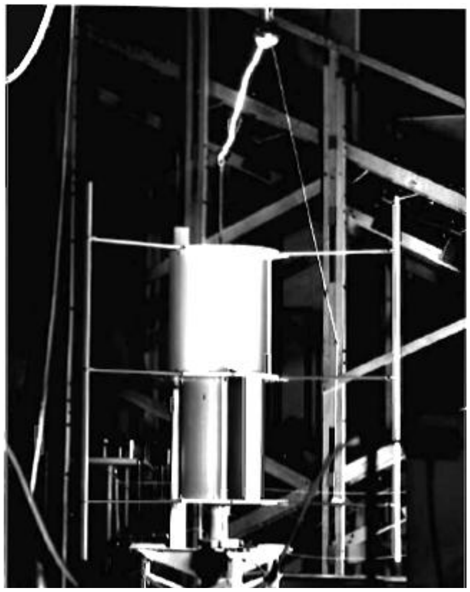


Fig- 9: The ERIGEN Turbine in Lighting strike test in a high voltage lab.

4.7 WTGS (combined Low speed and high speed rotor)

A new and unique counter rotating horizontal axis wind turbine system was introduced by Shinn, C. [18], which combines the conventional horizontal axis wind turbine (HAWT) system and the vertical axis wind turbine (VAWT) system by use of patented bevel-planetary gear arrangements.

An attempt has been made to analyse the aerodynamic performance of this rotor by Jung, S.N. et al. [119]. The percentage of power was increased by 20% in comparison with the baseline single – rotor configuration and it maximize up to 21 % at rated wind speed 10.6m/s. the power coefficient of reaches as high as 0.50. He was suggested that the power extraction from counter rotating(C/R) wind turbine is quite effective than the conventional single rotor.

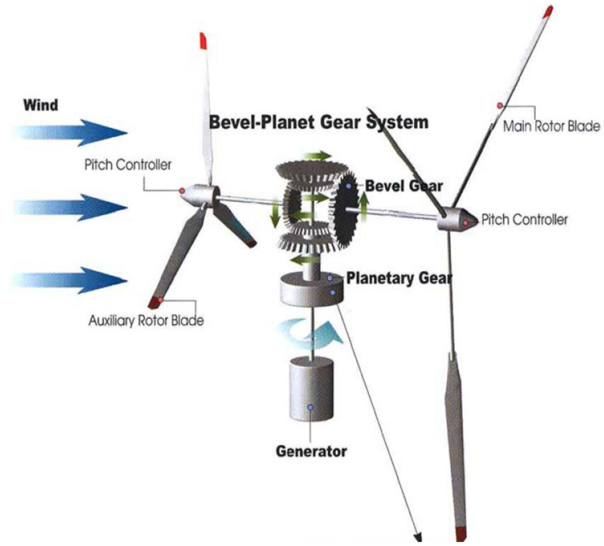
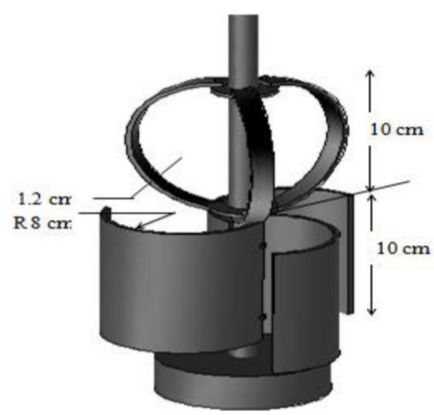


Fig- 10: Counter bladed horizontal axis turbine

4.8Three bladed combined Savonius Darrieus rotor

An attempt has been made to measure the performance of a three-bladed combined Darrieus-Savonius rotor, with Darrieus mounted on top of Savonius rotor [20]. This model is similar to discussed in section 3.1.3. However, there is changed in position of Savonius and Darrieus rotor and shown in Fig 11.

A wind tunnel experiment had conducted to carry out aerodynamic study with five overlap values 9.3 %, 13.8 %, 16.8%, 18.3% & 24.8%. The highest Cp value (0.53) of this rotor surpass that of the latter, which has a highest Cp of 0.51 obtained at a little higher TSR of 0.62 and optimum 16.8% over lap.



ISSN: 2250-3676
Volume-4, Issue-6, 453-463

Fig- 11: Three bladed combined Darrieus-Savonius rotor

4.9 Four bladed Darrieus and two stage Savonius Configuration

A hybrid turbine containing two stage Savonius rotor placed in middle with 4- bladed Darrieus had studied for marine current application by Alam, M.J et al. [21]. An innovated configuration is shown in Fig 3.9, in this prototype, both rotors are attached permanently on same shaft.

Fig- 12: Hybrid configuration of Darrieus and Savonius rotor

They studied the foam model of the hybrid turbine with maximum water testing speed 0.8 m/s due to structural strength concern. As the Savonius turbine was start up device provided maximum power 2.013 watt alone hybrid turbine generated power was 0.74 watt with 0.2 m/s. apart from this performance, the power generation of the designed prototype has led the Darrieus turbine up to 0.6 m/s. The maximum power achieved with the Hybrid configuration at 0.8 m/s is approximately 21.3 W. They had suggested, for a low power application. This hybrid unit can be used in parallel with other units, where the average current speed is around 0.5 m/s.

4.10 Three bladed semi elliptical Savonius and Darrieus rotor

A hybrid turbine with semi elliptical section of aspect ratio 0.8 Savonius rotor and Darrieus rotor have studied by Sahim, K. et al. [21]. An experimental prototype of hybrid Darrieus-Savonius is shown in Figure 3.10. Hybrid configuration was mainly analysed for coefficient of power and torque for different positions of semi elliptic buckets in experiment.

Fig- 13: Schematic diagram of Hybrid turbine.

It was found that two conFigurations of combined turbines for L = 0.79, β (attachment angle) = 60° and L = 0.36, β = 60° improve the torque at low speeds. One of these combined turbines, turbine with L = 0.36 and β = 60°, has higher coefficient of power. In addition, he recommended also that use of Savonius rotor make good start up for Darrieus rotor and also improve power coefficient. This turbine can be used efficiently in small water stream with less velocity 0.61m/s.

4.11 Three bladed straight Darrieus with two stage Savonius configuration

Letcher, T. [23] proposed a hybrid design of hybrid rotor of wind turbine for small scale wind applications he combined three bladed Darrieus rotor on top and two stage Savonius at bottom shown in Figure 3.11.

The Savonius blades were constructed from PVC pipe with JB Weld used to attach the blades to the aluminium plates. The Darrieus blades were custom made fiberglass blades. The hybrid turbine was tested in wind tunnel with constant speed (5, 8, 11, 13 mph). The analysis has been made with different blade profile NACA 0015(3" 0°), NACA 0015 (4.5"; 0°), S 2027(12"; 0°) and NACA 0015 (6", 0°). It was determined that the configuration that produced the most energy was the

ISSN: 2250-3676
Volume-4, Issue-6, 453-463

S2027 blade profile, with a 4.5" chord length, 0 degree pitch angle and 12" Darrieus diameter.
He compared hybrid turbine vs. WINDSPIRE turbine and found that more kWh has been produced using hybrid turbine of 12 ft. size than the 20 ft. WINDSPIRE Darrieus turbine [24].

Fig- 14: Representation of the hybrid turbine model

Table 2 Small-scale kinetic turbines rotor features

Turbine rotor	Darrieus (3-4 blade)	Savonius (1-2 stages)	Darrieus Savonius Hybrid Rotor
Power coefficient	0.23-.42	0.20-0.5	0.20-0.53
Torque coefficient	0.1-0.11	0.09-0.1	0.06-0.13
TSR	1.5-2.5	0.6-0.8	0.6-3.1

As seen from the Table 2 power coefficient has maximum for hybrid combination with TSR range 0.6-3.1. The coefficient of torque is enhanced to compare with other solo Savonius and Darrieus turbine.

5. DESIGN AND PERFORMANCE EQUATIONS OF HYBRID ROTOR

There are few studies has been carried out for analytical design and performance parameters of hybrid turbine. A design equation for 4-bladed Darrieus and two stage Savonius rotor has been found [21] and given as Eq. (1) and (2) for power output and TSR (Tip speed ratio) respectively.

$$P = 0.5 * \rho * V^3 \left(A_s C_{Ps} + (A_d - A_s) * C_{pd}\right) \quad (1)$$

$$\text{Tip speed ratio } (\lambda) = \frac{\omega R}{V} \quad (2)$$

Where, As = Swept area by Savonius rotor in m^2;
A_d = Swept area by Darrieus rotor in m^2;
Cps = Power coefficient of Savonius rotor;
Cpd = Power coefficient of Darrieus rotor;
ρ = Water density in kg/m^3;
ω = Shaft speed in rad/s;
λ = TSR of hybrid turbine;
R (R_d) = Maximum rotational radius;

A torque and power equations has been studied for three bladed eggbeater Darrieus and single stage Savonius rotor [24] and it given as follows:

$$Q_T = Q_s + Q_D \quad (3)$$

Where, Q_T is the torque of the combined machine; Q_S is the torque of the Savonius rotor; Q_D is the torque of the Darrieus rotor.

Total torque of combined machine mathematically as following

$$Q_T = \frac{1}{2}\rho A_T R_T C_{Qr} \quad (4)$$

And C_{Qr} can be calculated as follows:

$$C_{Qr} = C_{Qs}\frac{A_s D_s}{A_T R_T} + C_{QD}\frac{A_D R_D}{A_T R_T} \quad (5)$$

Where, R_D is the equatorial radius Darrieus turbine;
A_D is the swept area of Darrieus turbine;
D_S is the diameter of Savonius rotor;
R_T is the radius of the combined machine;
A_T is the swept area of the combined machine.

The power coefficient of combined machine has been evaluated as:

$$C_{Pr} = \lambda C_{Qr} \quad (6)$$

Where,

ISSN: 2250-3676
Volume-4, Issue-6, 453-463

C_{pr} is the Power coefficient of the combined machine. Tip speed ratio (λ) can be calculated by equation (2) for all configurations.

If we were to follow the formulation from equation (1) and (2), with the values of V=0.5 m/s, areas A_s=0.08m^2 and A_d=1m^2, and the density of medium ρ=1000kg/m^3, the maximum coefficient of power for Savonius and Darrieus rotors individually was found to be 0.2 and 0.34 respectively. However, upon implementation of the hybrid rotor combination of one of each type of rotor, the maximum coefficient of performance comes out to be 0.327 which is less than the peak performance of Darrieus turbine rotor employed individually, but it works well enough to bridge the requirement of high starting torque and power generation at lower rotational speeds for the same velocity of flow.

Table 3 Power coefficient of hybrid Darrieus- Savonius rotor

C_{ps}	λ_s	C_{pd}	λ_d	C_{ph}	P (kW)
0.047	0.100	0.300	4.620	0.281	18.985
0.083	0.203	0.307	4.690	0.290	19.603
0.128	0.322	0.312	4.750	0.298	20.120
0.161	0.452	0.317	4.840	0.305	20.618
0.187	0.554	0.321	4.930	0.311	21.006
0.198	0.667	0.328	5.150	0.319	21.520
0.200	0.740	0.332	5.270	0.322	21.753
0.194	0.859	0.337	5.540	0.327	22.053
0.178	0.961	0.339	5.640	0.327	22.082
0.161	1.029	0.340	5.880	0.327	22.057
0.142	1.080	0.337	6.390	0.323	21.775
0.117	1.147	0.332	6.610	0.316	21.317
0.092	1.187	0.329	6.770	0.311	21.007
0.063	1.238	0.322	6.820	0.303	20.459
0.033	1.260	0.320	6.880	0.299	20.162

An attempt has been made to determine performance characteristics of hybrid rotor using characteristics curves of various kinetic turbine rotors [9] and considering the equations (1) and (2). Different power coefficient of hybrid rotor has been calculated for different TSR. Velocity of flow and frontal area of Savonius and Darrieus has been taken as 0.5 m/s (water), 0.08 m^2 and 1 m^2 respectively. As seen from the table 2 the hybrid rotor have combined power coefficient slightly less than the Darrieus rotor and higher than the Savonius rotor. Using hybrid configuration the starting torque is increased. Maximum value of power coefficient has reached up to 0.327 for hybrid, 0.34 of Darrieus and 0.20 of Savonius.

6. HYDRODYNAMICS

There are two basic forces, act to the hybrid turbine rotor, drag and lift which result the torque generation at rotor shaft. The pressure difference in approaching blade geometry results a lift force and it drive the blade in forward direction. In order to propel the turbine, the net torque caused by lift forces must be greater than the net torque caused by drag forces [9]. It can be calculated as follows:

$$D = \frac{1}{2} C_D \rho A V^2 \qquad (7)$$

And lift force defined as:

$$L = \frac{1}{2} C_L \rho A V^2 \qquad (8)$$

Where, C_D= Drag Coefficient (0.045 for an Aerofoil);
C_L = Lift Coefficient;
A= Aerofoil/ Frontal Area.

The drag and lift forces mainly depended on Reynolds number and it can be represent as:

$$R_e = VL\frac{\mu}{\rho} \qquad (9)$$

R_e is Reynolds number, which is dimensionless,
μ is viscosity coefficient
V is the velocity of the Water in m/s.
L is the characteristic length, in this case the largest cross section of the frontal area in m.

7. SOLIDITY

The solidity of Darrieus rotor or Savonius rotor or even hybrid rotors takes suitable value, because of it force the high drag in case of water. It can be calculated as;

$$\sigma = \frac{C\,B}{\pi d} \qquad (10)$$

Where, C, B, and d are the chord length, the number of Blades and the turbine diameter, respectively.

2.1 Effective braking torque

To calculate the torque experimentally Sahim, K. et al. [18] used a rope brake dynamometer method. And it can be

ISSN: 2250-3676
Volume-4, Issue-6, 453-463

calculated from the measured load and spring balance load. The mathematically it can be defined as:

$$T = 9.81\,(W - S)\,\left(\frac{D_b + D_r}{2}\right) \qquad (11)$$

Where, D_b = Diameter of drum brake dynamometer (mm);

D_r = Diameter of rope (mm);
W = Dead load on brake (kg-f);
S = spring balance load (gr).

8. SIMULATION STUDY

A simulation model for combined-type straight-bladed vertical axis wind turbine (CT-SBVA WT) has been proposed by Li, Y. et al. [24] and this model is applicable for 2-D incompressible flow.
A study has been carried out to investigate velocity range and their performance parameter of available hybrid rotors and given in Table 4. It is observed that from Table 4, power coefficient is higher in case of wind turbine rotor than water turbine rotor and it was found 0.5 and 0.43 respectively.

Table 4 Flow velocity ranges of Various Hybrid rotors with power coefficients

Hybrid Configurations	Velocity Range (m/s)	Power Coefficient (Design point)
CT-SBVAWT	2.0-12.0 (wind)	0.2 (3.7m/s)
Eggbeater -Savonius (Type -A)	6.0-18.0 (wind)	0.204 (TSR 3.51)
Eggbeater -Savonius (Type -B)		0.231 (TSR 3.76)
Three straight Bladed Savonius - Darrieus	-	0.25 (TSR 0.28)
Two Bladed Darrieus and Savonius	1-5.5 (water)	0.43 (TSR 2.2)
Straight Bladed Darrieus -2 Stage Savonius	0.5-1 (water)	-
Erigen Combined Darrieus - Savonius	3-11 (wind)	0.16 (TSR 4.29)
Combined Low Speed -High Speed Rotor	1.8 -12.0 (wind)	0.5 (TSR 9.5)
4-Bladed Darrieus -2 Stage Savonius	0.5-0.8 (water)	0.15 (TSR 2.7)
Three Bladed Semi Elliptical Savonius Darrieus	0.6 -1 (water)	0.12 (TSR 1.4)
Three Straight Darrieus - 2 Stage Savonius	2.0-6.0 (wind)	0.19 (TSR 0.7)

In his study, numerical calculations were carried out by FVM method with combined-type straight- bladed vertical axis wind turbine. In order to computation, the continuity and momentum equation shown below:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho U_j)}{\partial x_j} = 0 \qquad (12)$$

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial xj} = \frac{\partial [\mu_e \{\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\}]}{\partial x_j} - \frac{\partial P}{\partial x_j} + S_i \qquad (13)$$

Where ρ is fluid density (kg/m^3) and the x_j is coordinate component, Ui and Uj are average relative velocity components, $\mu_e$is the significant viscosity coefficient, P is the pressure (Pa), S_j is the generated item.
To calculate the results of the equations, k-ε turbulence model was used as the turbulence model. Turbulent kinetic energy k (m^2/s^3) and turbulent energy dissipation rate ε were inducted. Therefore, the constraint equations were given as follows:

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_j)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + \rho (P_k - \varepsilon) \qquad (14)$$

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_j)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \frac{\rho \varepsilon}{k}(C_1 P_k - C_2 \varepsilon) (15)$$

Where, P_k is the turbulent kinetic energy generated term, and it is given as:

$$P_k = \frac{\mu_t}{\rho}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_i} \qquad (16)$$

This simulation model has been used many researcher to analysed the hybrid rotor configuration with different approach velocities and also performance of the rotor. It is powerful tool to attain brief knowledge about the rotor's flow dynamics.

9. CONCLUSION

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This paper gives a brief about the hybrid rotor which has been available in different configurations. Many attempts have been made to achieve a good start-up torque for hybrid rotor providing Savonius type rotor. A hybrid rotor configurations has been discussed for both water and wind energy generation. According to the study carried out, following conclusion can be made as follows:

- Power coefficient of kinetic turbine has been improved using hybrid rotor configuration up to 10 percent.
- According to the study, it is found that start-up torque of the combined rotor improved which facilitate low velocity installation of Darrieus- Savonius hybrid turbine.
- These hybrid rotors can be applied for small scale power generation (1kW- 50 kW) in remote and standalone areas.
- The theoretical and mathematical model gives a better understanding of the design and performance of the hybrid rotor and it can also provide a comparative study with the conventional single rotor.
- A model study of the combine rotor may establish a performance evaluation of study of the hybrid turbine with different conditions of the parameters.

In addition, all concept of hybrid rotor design provide an innovative approach to develop efficient kinetic turbines.

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