Performance Measurement of a Three-Bladed Combined Darrieus-Savonius Rotor

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Abstract- Combination of Savonius and Darrieus type Vertical Axis Wind Turbine (VAWT) rotors possess many advantages over their individual designs, like low starting torque, high power coefficient, low cut-in wind speed etc. However, there is still a need to do more research on such combination of rotors for their viability in the built environment where wind speed is low. In this paper, an attempt is made to measure the performance of a three-bladed combined Darrieus-Savonius rotor, with Darrieus mounted on top of Savonius rotor, for overlap variations from 10.8% to 25.8%. Power coefficients (Cp) and torque coefficients (Ct) were calculated in a low range of Tip Speed Ratio for each overlap condition. It is found that Cp increases with the increase of overlap. However, there is an optimum value of overlap for which, Cp is maximum, beyond this, Cp starts decreasing. The similar trend is observed for Ct as well. The maximum Cp of 0.53 is obtained at 0.604 Tip Speed Ratio (TSR) for an optimum 16.8% overlap. The performance of the rotor is also compared with another version of this hybrid design with Savonius mounted on top of Darrieus rotor. The present Darrieus-Savonius rotor can be suitably placed in the built environment where it can harness more power from wind and, at the same time, would self-start in low wind condition prevalent in such environment.

Keywords- Combined Darrieus-Savonius rotor, overlap, low tip speed ratio, power coefficient, torque coefficient

1. Introduction

Wind is an environment friendly source of energy that has got huge potential of satisfying the energy needs of people and mitigating the climate change from greenhouse gases, emitted by the burning of fossil fuels. It was estimated that roughly 10 million MW of energy are available in the earth's wind [1]. The potential of wind energy is reflected in the increase of capacity growth of wind energy systems. As of now, the installed capacity of wind energy system in the world is 194,390 MW [2]. Wind can be tapped by wind turbines that convert its kinetic energy into mechanical power, which is in turn converted into electricity by generator of the wind farm. Wind turbines are of two types, Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). VAWT is mostly viable for places with low wind speed regimes where HAWT is highly uneconomical. Further, VAWT rotors do not require any yawing facility that brings the plane of the blades to the wind direction, as required in case of HAWT. However, the major drawback of VAWT is its low performance coefficients. Hence there is a scope for major research on VAWT rotors to improve their performance. The present work is based on VAWT rotor. VAWT rotors are of different types, like Savonius, helical Savonius, Eggbeater Darrieus, H-Darrieus, combined configurations of Savonius and Darrieus rotors etc.

Savonius rotor, also called S-rotor, was originally invented and patented by Finnish Engineer Sigurd J. Savonius in 1931. Savonius [3] investigated the performances of 30 different models of the S-rotors in the wind tunnel. Tests were conducted in open-air as well. He reported a maximum power coefficient (Cp) of 0.31 from wind tunnel investigations while reported a maximum Cp of 0.37 from open-air tests. Between Sixties and the last decade, many researchers [4-16] had investigated experimentally the performances of different designs of Savonius rotor and obtained their Cp in the range of 0.15-0.38. Darrieus rotor is a type of VAWT originally invented and patented by G.J.M. Darrieus in 1931 [17]. It has two or three curved blades with aerofoil cross-section of constant chord length. Both ends of the blades are attached to a vertical shaft, which is well supported at the base (fig.1). When rotating, these blades provide a torque about the central shaft in response to a wind stream. Darrieus rotor is usually a non-self-starting wind rotor but it provides good power coefficient after its cut-in speed. For this reason, Darrieus rotor is not used alone; rather it can be used in combination with Savonius rotor that accepts low starting torque. The combination of Savonius and Darrieus rotors has better performance than individual Savonius or Darrieus rotors since it combines low starting torque requirement of Savonius & high power coefficient of the Darrieus rotor. Elmabrok [18] measured the performance of a combined Darrieus-Savonius rotor experimentally and computationally. The Darrieus rotor was made from wooden blades and was a three-bladed system, which was combined with two-bladed Savonius rotor. In the computational method, the performance was determined using the multiple stream tube theory. The results for the individual rotors were then combined to determine the resultant performance of the combined rotor. The experiments were conducted in a subsonic wind tunnel. The comparisons of results between the experimental and computational approaches were in good agreement. A maximum Cp of around 0.34 was obtained at without overlap condition. Gavalda et.al. [19] measured the performance of a self-adapting combined two-bladed Savonius-Darrieus rotor with Savonius rotor mounted on top of Darrieus rotor. A maximum Cp of 0.35 was reported at 16% overlap. Gupta et al. [20] experimentally evaluated the performance of a combined two-bucket Savonius and three-bladed Darrieus rotor within overlap range of 16.2%-25%. A maximum Cp of 0.25 was obtained at 20% overlap at a low tip speed ratio of 0.32. Gupta et al. [21] again made a comparative study between a three-bucket Savonius rotor & a combined configuration of a three-bucket Savonius and three-bladed Darrieus rotor within overlap range of 16.2%-35%. The maximum Cp of the combined rotor without blockage effect was higher than the Savonius rotor, and it was reported to be 0.51 at a low tip speed ratio of 0.61.

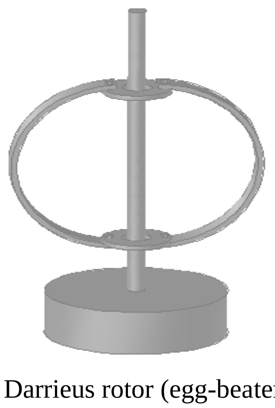

Fig. 1. Darrieus rotor (egg-beater type)

Thus, from the above literature, it is understood that-

a) Only few works have been reported on the combined designs of VAWT rotors in low wind speed condition.

b) Combined design of Savonius and Darrieus rotors exhibit better power coefficient than individual Savonius or Darrieus rotor.

c) And three-bladed design of the combined Savonius Darrieus rotors have higher power coefficient than their two-bladed designs.

Considering all these, in this paper, an experimental study has been conducted in an open circuit subsonic wind tunnel to measure the performance of a three-bladed combined Darrieus-Savonius rotor within a low range of Tip Speed Ratio. The overlap variations are taken between 10.8% and 25.8%. The Darrieus rotor has been mounted on top of the Savonius rotor in the present design.

2. Physical Model

The model of three-bladed combined Darrieus-Savonius rotor was designed and fabricated in the workshop of the department. Three-bladed Darrieus rotor was mounted on top of three-bladed Savonius rotor. The blades of the Savonius rotor were 8 cm in chord, 3 mm in thickness and 10 cm in height. The Darrieus rotor in the combined configuration was made up of aluminum semi-circular blades of chord 12 mm, thickness 3 mm, height 10 cm. Therefore, height of the combined rotor was 20 cm. The rotor was mounted on a central shaft of 1.5 cm diameter and 25 cm height, which was well supported by ball bearings within a base. The ball bearings were washed in petrol to reduce their friction. The base was 7 cm in diameter and 2.4 cm thick. Washers & nuts having knurled surfaces was used to create overlap in the blades of the Savonius. Five overlap conditions namely 9.3%, 13.8%, 16.8%, 18.3% and 24.8% etc were obtained. Overlap is the distance of the inner edge of the blade from the axis of rotation assuming the arc is carried to the full semi-circle. The schematic diagram of the three-bladed combined Darrieus-Savonius rotor is shown in fig.2.

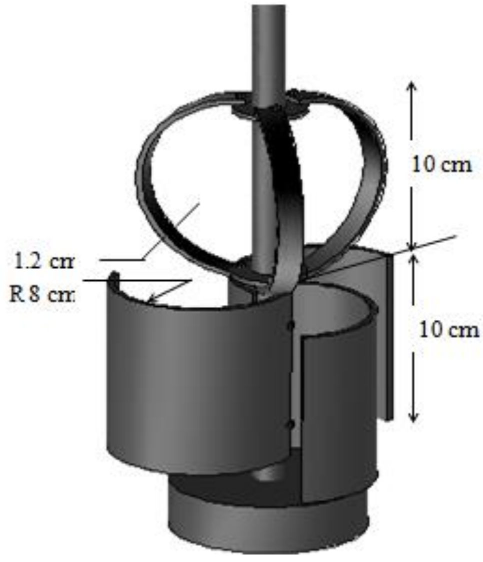

Fig. 2. Physical model of 3-bladed combined Darrieus-Savonius rotor

3. The Wind Tunnel

Experiments were conducted in an open circuit subsonic wind tunnel available in the department (fig.3). The size of the wind tunnel test section was 30 cm x 30 cm, and length of the test section was 3 metres. The operating range of the wind tunnel was 0-35 m/sec. The wind tunnel was operated by a centrifugal blower having 15 kW capacity motor with axial flow fan that supplied 6700 cubic feet per meter at rated 2890 rpm. The turbulence intensity of the wind tunnel was around 1%. The flow was uniform in the test section within 1% variation of wind speed in the width direction of the test section. The brief description of the subsonic wind tunnel can be found in the literature [20].

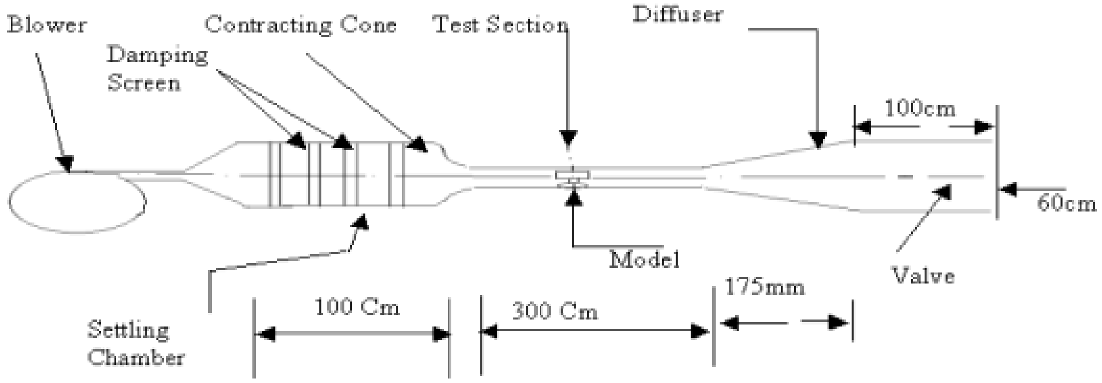

Fig.3. Schematic layout of open circuit subsonic wind tunnel

3.1. Instrumentations

(a) Pitot static tube:

Pitot static tube is one of the most accurate devices used for measuring wind speed when the turbulence level is low. There was a traversing mechanism by which pitot-static tube was traversed vertically and horizontally. Pitot static tube has a 90° bend of a shorter length. In this, the static tube surrounds the total head tube, and two or more holes are drilled radially through the outer wall into the annular space. The inner tube is provided with a small-drilled hole called nose. Outlets from the inner tube and the outer tubes are connected to different limbs of U-tube manometer filled with water. When the bent end is directed upstream, the velocity of the fluid particles facing this nose becomes zero and a stagnation point is created immediately ahead of the nose. For the subsonic flow, the stagnation pressure at the nose of the body is very closely equal to the total head in the stream tube leading to the stagnation point.

(b) U Tube manometer:

This measures unknown pressure by balancing against the gravitational force of the fluid heads. The manometer is filled with water whose specific gravity is unity. Both the limbs of the U-tube manometer are provided with wooden scales. One limb measures the total or stagnation pressure while the other measured the static pressure. The difference between these pressures is a measure of dynamic pressure, which is a function of wind speed as given in eqn 1. Wind speed was adjusted by controlling the gate opening at the exit of the wind tunnel. The turbine was allowed to rotate from no load speed.

$P_s + 0.5*\rho*V2 = P_t$

$$\Rightarrow V = \sqrt{\frac{2*(P_t - P_s)}{\rho}} \qquad [1]$$

Where, P_s = static pressure

P_t = total or stagnation pressure

V = wind speed

(c) Tachometer

The rotor rpm was measured by a digital tachometer having least count 1 rpm.

4. Experimental Approach

The performance of a wind rotor can be expressed in the form of power coefficient (Cp) versus Tip Speed Ratio, TSR (l), and the torque coefficient (Ct) versus TSR at various overlap ratio conditions. Power coefficient is the ratio of power produced by the rotor to the maximum wind power (eqn 2). The power produced by the rotor, Protor, is calculated as the product of aerodynamic force transmitted by the bucket of the rotor (1/2 ρAV12) and speed of blade (u) as given in eqn 3. The aerodynamic force is measured as the ratio of rate of change of angular momentum of wind in the advancing stroke of the rotor at inlet of the test section to the radius of the rotor. In the downstream side wake velocity, being small, its effect is neglected in the calculation of rate of change of angular momentum across the rotor. In the present case, readings are taken in the steady-state flow conditions. The aerodynamic torque was calculated from the standard relationship of power and torque (eqn 4).

$$C_p = \frac{P_{rotor}}{P_{\max}} \qquad [2]$$

$$P_{rotor} = \left(\frac{1}{2}\rho A V_1^{\,2}\right) u$$

$$= \left(\frac{1}{2}\rho A V_1^{\,2}\right)\frac{\pi D N}{60} \quad [3]$$

$$T = \frac{60 P_{rotor}}{2\pi N} \quad [4]$$

The wind power with blockage effect is represented as below:

$$P_{max} = \frac{1}{2}\rho A V_{free\_block}^{3} \quad [5]$$

Where Vfree_block is the free-stream velocity with blockage as represented in eq^{n} 6 below:

Vfree_block = Vfree * (1+ε) [6]

Where 'ε' is the wind tunnel blockage correction factor due to combined solid and wake blockages. When a rotor is placed in the test section of wind tunnel, it creates hindrance or blockage to the flow, which increases the local free stream wind speed in the test section. In wind tunnel testing, the blockage effect needs to be taken into account to determine the actual power produced by the rotor. The total blockage correction factor [22] due to combined solid and wake blockages is given as

$$\varepsilon = \frac{1}{4}\frac{HD}{H'W} \quad [7]$$

The torque coefficient is evaluated as the ratio of power coefficient to the tip speed ratio as shown below:

$$C_t = \frac{C_p}{\lambda} \quad [8]$$

Where tip speed ratio, λ can be expressed as given eqn9:

$$\lambda = \frac{u}{V_{free}} \quad [9]$$

Where 'u' is the blade speed and Vfree is the free-stream velocity

5. Experimental Results

The experimental results of the three-bladed combined Darrieus-Savonius rotor were obtained for five overlap values, namely 9.3%, 13.8%, 16.8%, 18.3% & 24.8%. The variations of power and torque coefficients with Tip Speed Ratio at different overlaps are shown from fig.4 to fig.8. Figure 9 shows the comparative plot of the variation of power coefficient with respect to Tip Speed Ratio between the present three-bladed Darrieus-Savonius rotor and a three-bladed Savonius-Darrieus rotor of identical designs with Savonius mounted on top of Darrieus rotor as investigated by Gupta et al. [21].

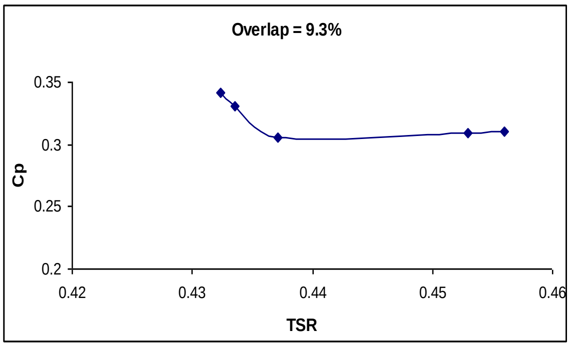

Fig. 4 (a). Variation of Cp with TSR for 3-bladed combined Darrieus- Savonius rotor at 9.3% overlap

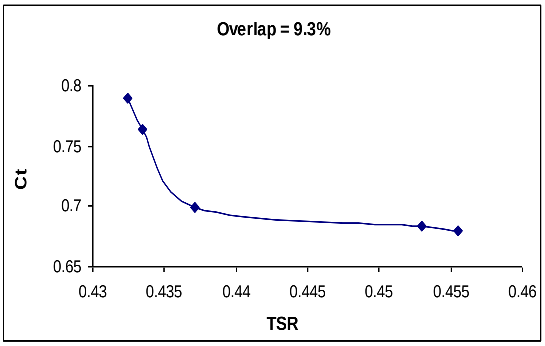

Fig. 4 (b). Variation of Ct with TSR for 3-bladed combined Darrieus-Savonius rotor at 9.3% overlap

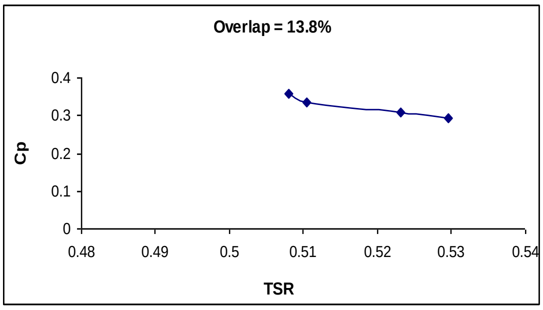

Fig. 5 (a). Variation of Cp with TSR for 3-bladed combined Darrieus- Savonius rotor at 13.8% overlap

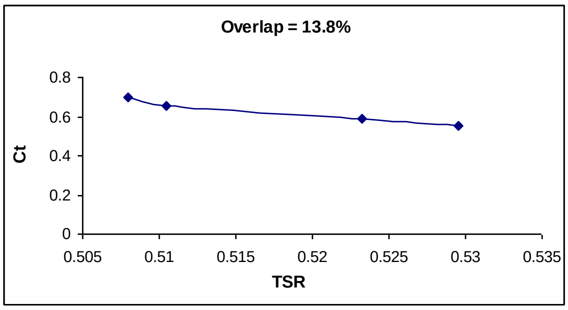

Fig. 5 (b). Variation of Ct with TSR for 3-bladed combined Darrieus-Savonius rotor at 13.8% overlap

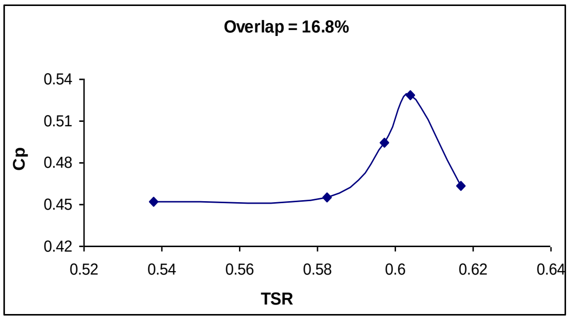

Fig. 6 (a). Variation of Cp with TSR for 3-bladed combined Darrieus- Savonius rotor at 16.8% overlap

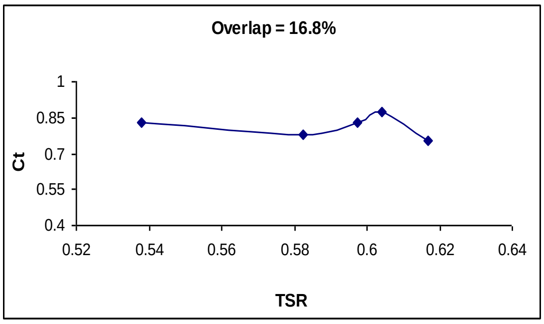

Fig. 6 (b). Variation of Ct with TSR for 3-bladed combined Darrieus-Savonius rotor at 16.8% overlap

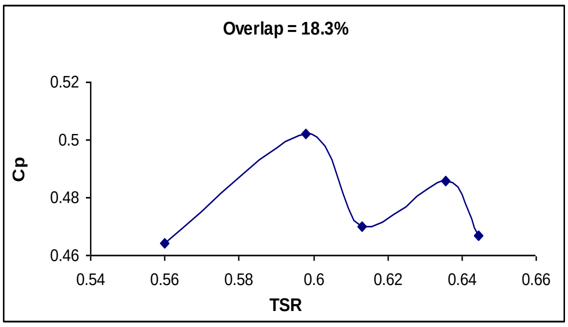

Fig.7 (a). Variation of Cp with TSR for 3-bladed combined Darrieus- Savonius rotor at 18.3% overlap

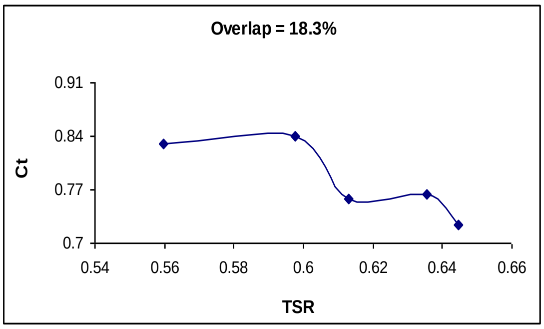

Fig.7 (b). Variation of Ct with TSR for 3-bladed combined Darrieus-Savonius rotor at 18.3% overlap

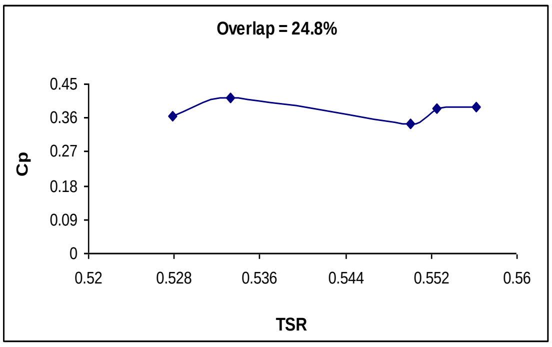

Fig. 8 (a). Variation of Cp with TSR for 3-bladed combined Darrieus-Savonius rotor at 24.8% overlap

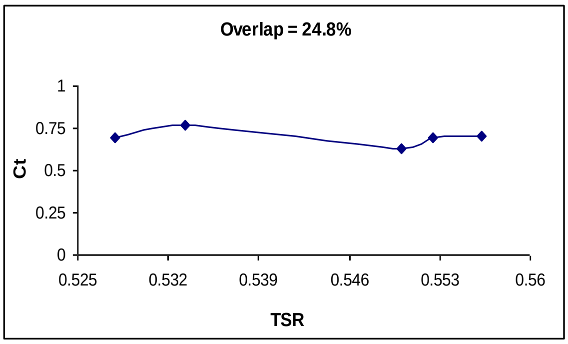

Fig. 8. (b). Variation of Ct with TSR for 3-bladed combined Darrieus-Savonius rotor at 24.8% overlap

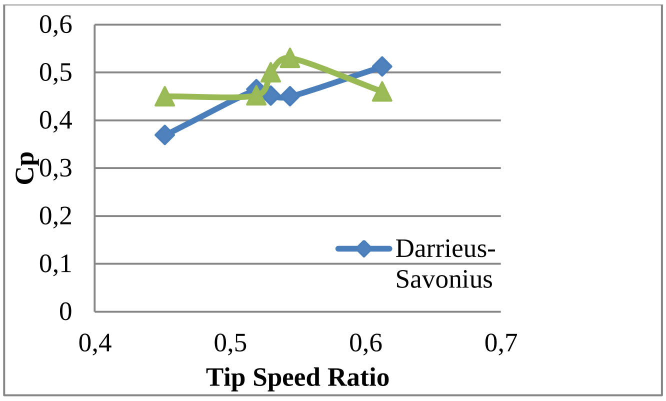

Fig.9. Comparison of Cp with TSR between the present rotor and a three-bladed Savonius- Darrieus rotor [21]

Both power coefficients (Cp) and torque coefficients (Ct) increase with the increase of Tip Speed Ratio (TSR) up certain limit and then decrease with further increase of the latter. Thus there is an optimum value of TSR for which the power & torque coefficient are the maximum for the rotor. For 9.3% overlap, the maximum Cp of 0.34 is obtained at a TSR of 0.432 (fig.4a), and the maximum Ct of 0.79 is obtained at a same TSR of 0.432 (fig.4b). For 13.8% overlap, the maximum Cp of 0.35 is obtained at a TSR of 0.508 (fig.5a), and the maximum Ct of 0.70 is obtained at a same TSR of 0.508 (fig.5b). For 16.8% overlap, the maximum Cp of 0.53 is obtained at a TSR of 0.604 (fig.6a), and the maximum Ct of 0.87 is obtained at a same TSR of 0.604 (fig.6b). For 18.3% overlap, the maximum Cp of 0.50 is obtained at a TSR of 0.597 (fig.7a), and the maximum Ct of 0.84 is obtained at a same TSR of 0.597 (fig.7b). For 24.8%

overlap, the maximum Cp of 0.41 is obtained at a TSR of 0.533 (fig.8a), and the maximum Ct of 0.77 is obtained at a same TSR of 0.533 (fig.8b). Thus, with increase of overlap from 9.3% to 16.8%, Cp increases to the maximum, but afterwards for overlap variation from 18.3% till the end, Cp gradually decreases. There is an optimum value of overlap for which Cp is the maximum for the rotor, which is 16.8%. The trend is same in the variation of Ct with overlap also. Now finally, fig.9 shows that the present results of Cp at different TSR values compete quite well with those of Cp values for three-bladed Savonius-Darrieus rotor as obtained by Gupta et al. [21]. Moreover, the highest Cp value (0.53) of the present rotor surpass that of the latter, which has a highest Cp of 0.51 obtained at a little higher TSR of 0.62. Hence, it is verified that the three-bladed combined designs of Darrieus-Savonius or Savonius-Darrieus rotors exhibit higher value of power coefficient compared to their individual design performances. Therefore, such hybrid design of Darrieus-Savonius rotor can be suitably placed in the built environment where it can harness more power from wind and, at the same time, would self-start in low wind conditions as present in such environment.

6. Conclusion

In this paper, an attempt was made to measure the performance of a three-bladed combined Darrieus-Savonius rotor with Darrieus mounted on top of Savonius rotor, for overlap variations from 10.8% to 25.8% in a low TSR range. The following conclusions are summarized from the study:

i) Both power and torque coefficients increase with the increase of TSR up to the maximum and then both decrease with further increase of the latter. Therefore there is an optimum TSR at which the performance coefficients are the highest.

ii) Similarly power and torque coefficients increase with the increase of overlap up to the maximum and then decrease giving an optimum overlap at which the performance coefficients are the highest.

iii) The maximum Cp of 0.53 is obtained at a TSR of 0.604 at an optimum 16.8% overlap, which is higher than the conventional Savonius rotor or three-bladed combined Savonius-Darrieus rotor [21].

The present Darrieus-Savonius rotor can be suitably placed in the built environment where it can harness more power from wind and, at the same time, would self-start in low wind condition prevalent in such environment.

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