A Design for High-Torque, Low-Speed Vertical Axis Wind Turbine

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Abstract Since last few years, there has been an enormous thrust on the development of alternative energy sources to cope up with the diminishing reserves of conventional energy resources. Because of its continuous availability, wind happened to be element for conversion into an alternative energy resource. The design of high-power wind turbine has geared up to the requirement, but unfortunately there are not much literature that contain any functional design for low-speed, high-torque micro-wind power generation system. In this paper, a methodology has been presented for the design of vertical axis wind energy conversion systems suitable for low-power domestic purposes. This design facilitates the manufacturer to easily select the turbine blade tilt angle and the ratio of overall L/D. This design is based on the Gorlov helical structure concept applied to Savonius turbine. A workbench for the simulation has been developed, and the design is simulated. The vertical axis turbine that is designed avoids the use of gearbox, and it is more suitable for direct mounted generation system.

Keywords Savonius helical turbine · Gorlov principle · Airfoil
Vertical axis wind turbine · Direct coupled generator · Tip speed ratio

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1 Introduction

Power generation through wind is a new swing from conventional energy sources, in which reliable power generation and cost saving are the main criteria. In the process, maximum effort is taken to reduce the noise level and meet the load demand. Based on the orientation of the axis, turbines are classified into horizontal axis and vertical axis turbine. The horizontal axis turbine is more common over the decade; in the installation the first and foremost problem is, it occupies a huge area, required large capacity of cranes to mount on the surface and needed more men power. The HAWT should be oriented towards the wind direction by the yaw mechanic control technique, and the aerodynamics of the horizontal axis is very complex. Many VAWT are proposed in recent times in which Darrieus and Savonius turbines are most common. Keeping with the view of a few aspects such as self-starting and uniform torque distribution along the turbine with vibration free, where the Darrieus and Savonius turbines fail to attain, a new Savonius helical turbine is designed.

Gorlov [1] developed a helical turbine designed for low fluid flow rates in the 1990s. It was initially developed for use in water either in a slow river or as a tidal generator. This turbine uses a vertical axis configuration having three blades that are swept along a helical path. Using this configuration, the turbine will always rotate in the same direction, regardless of the direction of the fluid flow. With its small size and intended to apply for low wind speeds, Gorlov helical turbine is a prime candidate to fill the need for a portable wind turbine. By using the idea of Gorlov helical turbine, a Savonius helical twist turbine is designed for self-start and uniform torque distribution. The turbine size as a function of power is required to drive a permanent magnet generator.

This paper is organized as follows. Second section elobertaes the Power calculation for VAWT from the literature. The next section gives an idea of the problems associated with VAWT design, particularly Savonius helical turbines. The obtained CFD analysis results for various designs are compared and the adaptable configuration is chosen from analysis data.

2 Power Equations of VAWT

The maximum power that can be extracted is given by [2] (Fig. 1)

$$P_{\max} = C_0 \rho R_0 H(V^3) \tag{1}$$

where C_0 = power coefficient = 0.3ρ = density of air = 1.225.

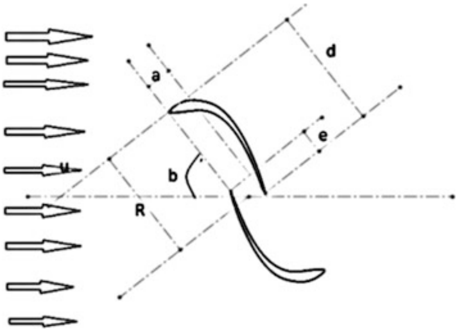

Fig. 1 Airfoil isometric view and wind force directions

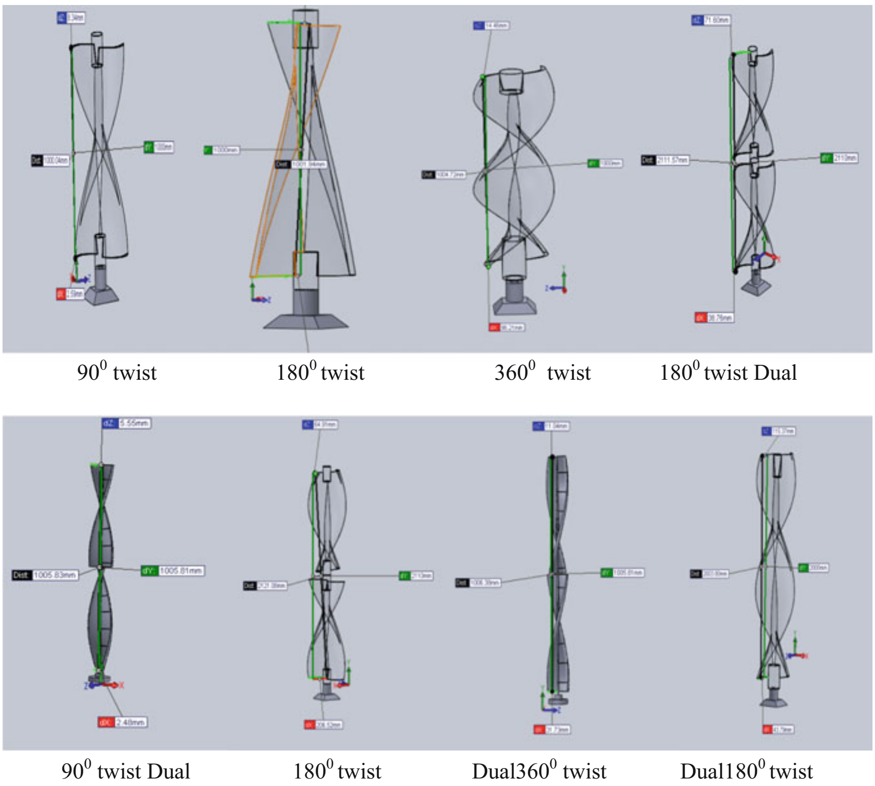

Fig. 2 Different combinations of Savonius helical twist turbines

Generally, Assuming tip speed ratio = 1 and we get

$$\lambda = \left(\frac{\omega r}{V_{\mathrm{w}}}\right) \tag{2}$$

$$\text{Torque} = \left(\frac{P_{\max}}{\omega}\right) \tag{3}$$

For example, with diameter D of 480 mm, using the empirical relation $2d - e = D$; $m = e = (d/6)$; then $e = a = 51$ mm, $d = 265.5$ mm and $L = 1000$ mm.

The data considered for the simulation are shaft diameter D: 100 mm. Bearing type: roller.

The generator chosen was permanent magnet synchronizing generator with voltage rating of 12 V and 100 rpm so as to achieve direct drive generator.

2.1 Designed Models of Savonius Helical Twist Turbines

See Fig. 2.

3 Stated Problem

The problems identified in the literature [3, 4] existing on VAWT were as follows

- At low speeds, there is a lack of lift generated in the turbine and uneven torque distribution, and the Darrieus turbine fails to self-start
- The Savonius While self-starting has very low efficiency.

The uneven torque distribution of Darrieus turbine has been addressed in a design known as Quiet Revolution turbine, which is based on Dr Gorlov's Helical Turbine.

3.1 Proposed Elucidation

Savonius turbine blades to be twisted helical for solving the uneven torque distribution, and the assembly of 2 or 3 blades will be incorporated to provide the starting torque for the turbine which in turn makes the turbine self-starting [5–7]. With different wind velocities, the model is tested.

3.2 Steps to Be Taken

- Designing the blades based on the application in rural and domestic environment with the limitation of size.
- Designing the complete airfoil section of the blade where the angle attack is same throughout the blade in order to achieve noise-less rotation.
- Prototype manufacturing based on the newly proposed concepts.
- Testing using solid work flow simulation by creating a virtual wind tunnel where environmental pressure acts.

3.3 Flow Simulation

The design software for flow simulation is very much suitable for engineer who needs flow analysis [8]. A goal-oriented approach easily allows for gaining insight into the performance of design under real environmental conditions in less time.

4 Computational Fluid Dynamics Analysis

The wind tunnel environment is created for the design turbine model to study the flow simulation characteristics on the CFD work bench. The environment constraints like wind direction and environmental pressure are given as boundary conditions to flow simulation, the virtual environment is achieved equivalent to a real time scenario.

Objective of testing is

- To test the best helical twist turbine, the model of one blade with dimensions is tested at different wind velocities by creating a wind tunnel in CFD analysis.
- The testing is done in two phases; first phase includes the testing the best twist for a unique turbine, and the second phase includes by varying the L/D ratio of the turbine (Fig. 3).

Tip speed ratio impact on turbine dimensions

CFD flow analysis tip speed ratio of Savonius turbine is observed to be 1, since the wind tunnel environment is created bounded with environmental pressure acting

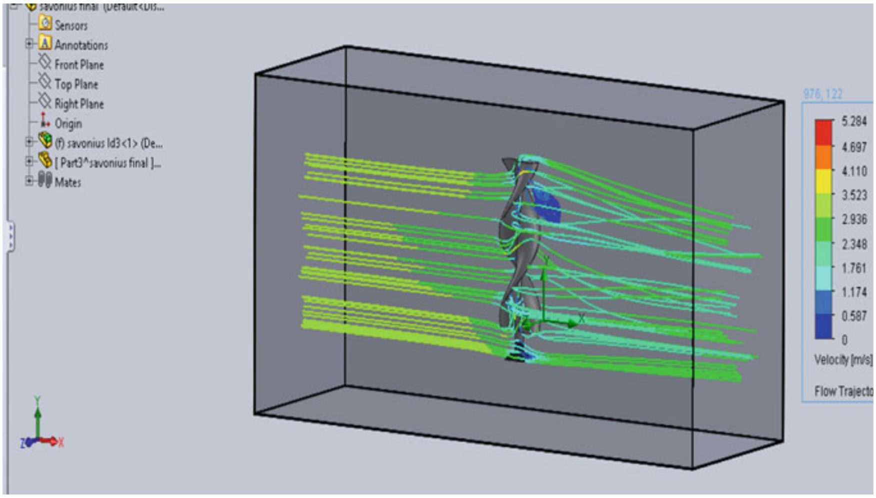

Fig. 3 Flow simulations for 360 twist blade turbine, L/D = 3

opposite to the direction of the wind flow. The tip speed ratio is (TPR) 0.833, which is near to 1.0; therefore, the tip speed ratio of Savonius turbine is confined to 1.0 [9, 10].

5 Results and Discussion

Case (i) **Savonius turbine tested with different twist angles**

In this the turbine dimensions of diameter 0.5 m and height 1.0 m with a helical twist of 90°, 180°, 360° are designed. The turbine is tested in a wind tunnel with the flow simulation tool. The turbine behaviour for different wind conditions is observed and conclusions are derived with a goal oriented to obtain a turbine which suits micro-power generator parameters (Table 1).

Figure 4a shows that wind power and shaft power developed by wind turbine with respect to wind speed. From Fig. 4b, the torque obtained by the 90° twist helical turbines is maximum as compared to that of 180° and 360° twist.

The 180° twist turbine attains high shaft speed at different wind velocities as that of 90° and 360° twist turbines as shown in Fig. 5a. Speed and torque characteristics of wind turbine with 360° helical twist have a large variety of operating conditions with variable wind velocities as shown in Fig. 6. Hence the turbine with blade twist of 360° is chosen for further analysis by varying the dimensions, i.e. L/D ratio of the turbine.

Table 1 Turbine shaft speed, torque variation for different configurations

Blade twist (deg)	Wind speed (m/s)	Wind power (w)	Power extracted (w)	Torque (Nm)	ω (rad/s)	Turbine speed (rpm)
90	3	24.14	7.24	1.42	5.09	48
180	3	24.14	7.24	0.415	17.44	166
360	3	24.14	7.24	0.729	9.93	94
90	5	111.78	33.53	4.04	8.29	79
180	5	111.78	33.53	2.93	11.44	109
360	5	111.78	33.53	2.133	15.71	150
90	7	306.72	92	7.904	11.63	111
180	7	306.72	92	3.297	27.90	266
360	7	306.72	92	4.144	22.2	212
90	10	894.25	268.27	16.03	16.73	159
180	10	894.25	268.27	6.699	40.04	382
360	10	894.25	268.27	8.384	31.99	305
90	15	3018	905.4	35.979	25.16	240
180	15	3018	905.4	14.749	61.38	586
360	15	3018	905.4	18.576	48.74	465

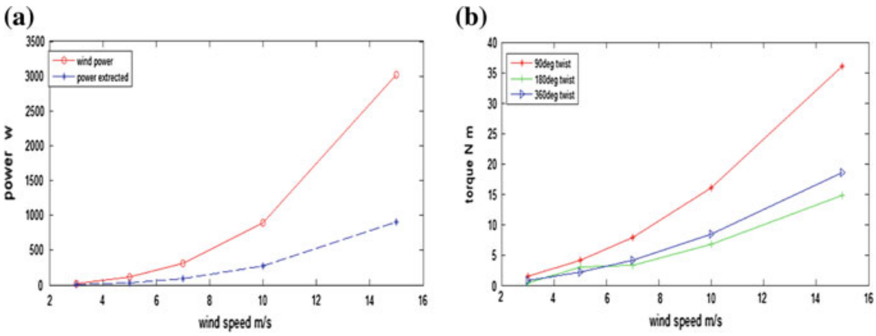

Fig. 4 **a** Wind power, shaft power extracted variation as a function of wind speed **b** turbine shaft torque versus wind speed for different twists

Case (ii) **Testing of turbine with different L/D ratio**

The Savonius two-blade turbines with 360° twist with different heights are considered by keeping the radius as constant. The turbine with more sweeping area acquires (turbine with high L/D ratio) more power and torque, but the limitation on shaft speed. So confining to size constraints for the different combinations of parameters, a suitable model has to be finalized. For L/D ratio 4, the turbine acquires high torque compared to other configurations as shown in Fig. 6a. For L/D

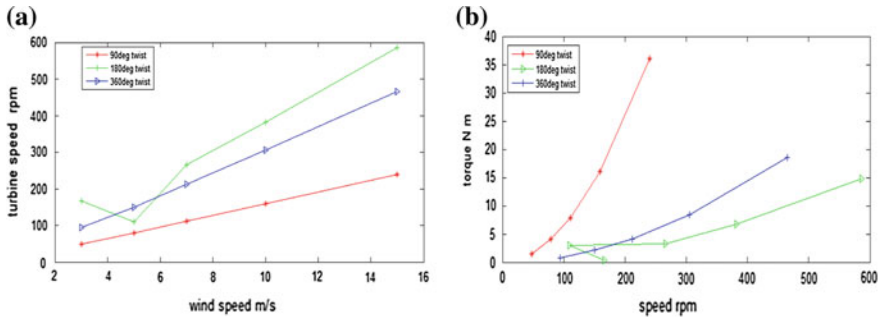

Fig. 5 **a** Turbine shaft speed versus wind speed for different twists **b** shaft speed, shaft torque cumulative variation for different twist angles

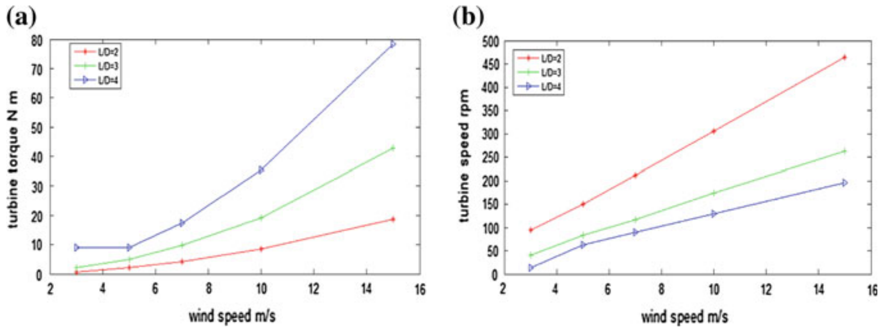

Fig. 6 **a** Torque versus wind velocities with different L/D ratios, **b** shaft speed variation w.r.t to wind velocities for different L/D ratio

ratio 2, the turbine attains high speed compared to other turbines for different wind velocities as shown in Fig. 6b (Table 2).

Therefore, when an average wind speed is in the range of 5 m/s and L/D as 3.0, i.e. dimensions of the turbine are optimum for a length of 1.5 m and a diameter of 0.5 m with a shaft torque of 4.973 Nm at shaft speed of 83 rpm. For the obtained turbine parameters, it is evident that the turbine can be used to drive direct coupled generator. The obtained torque is enough to drive the generator. Thus, with the considerable elimination of gear train, the turbine efficiency is improved (Fig. 7 and Table 3).

The designed Optimum turbine model is simulated with direct coupled Axial flux permanent magnet (AFPM) generator. For the Designed turbine shaft torque a AFPM machine is modelled using the dimensional equations and it is simulated in powergui template, to verify the specifications of Generator. The Matlab simulation incorporate with design turbine and AFPM with a three phase bridge rectifier and Buck boost converter.

Table 2 Turbine shaft speed, torque variation w.r.t to L/D ratio

L/D ratio	Wind speed (m/s)	Wind power (W)	Power extraction (w)	Torque (Nm)	w (rad/s)	Turbine speed (rpm)
2	3	24.14	7.242	0.729	9.93	94.91
3	3	31.42	9.42	2.243	4.199	40.12
4	3	42.99	12.897	9.028	1.428	13
2	5	111.78	33.53	2.133	15.71	150
3	5	145.46	43.63	4.973	8.77	83
4	5	199.06	59.718	9.048	6.6	63
2	7	306.72	92.016	4.144	22.20	212
3	7	399.16	119.74	9.731	12.30	117
4	7	546.22	163.866	17.516	9.355	89
2	10	894.25	268.27	8.384	31.99	305
3	10	1163.75	349.125	19.106	18.27	174
4	10	1592.5	477.75	35.345	13.51	129
2	15	3018	905.4	18.576	48.74	465
3	15	3927.65	1178.29	42.848	27.499	262.72
4	15	5374.68	1612.40	78.420	20.56	196

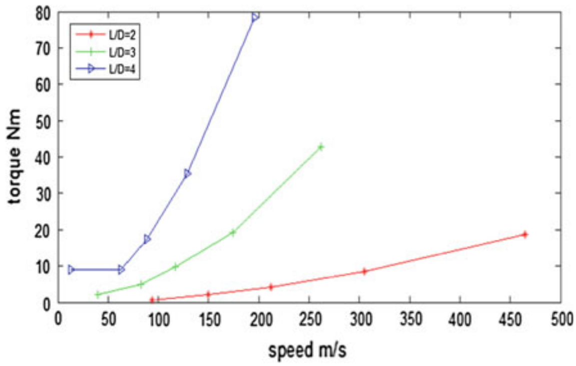

Fig. 7 Shaft torque and speed cumulative variation with L/D ratio variation

Figure 8a represents the voltage of the Simulink model, *x* axis and *y* axis represent time and DC voltage, respectively. As the wind velocity increases, the power generated also increases, The model designed as the survival speed to operate at 15 m/s. Figure 8b represents the current of the model, where x axis and y axis represent time (s) and current, respectively. The power obtained is nearly 814 W which serves the need of domestic and lighting usages. These models can be extended to the required design from end-to-end analysis.

Table 3 Slotted PMSG final design dimensions and specifications

Output power	P_{out} (W)	1000	Speed	N (rpm)	100
Output DC voltage	V_{dc}	24	Frequency	F (Hz)	15
Number of poles	P	18	Number of slots	Ns	162
Fundamental winding factor	K_{wl}	0.966	Air gap	g (mm)	1
Magnetic loading	B_g (T)	0.79	Electric loading	A (LA/m^2)	
Outer diameter	D_0 (m)	0.25	Inner/outer diameter	L	0.53
Pole arc/pole pitch	α_p	0.65	Magnet thickness	L_{pm} (mm)	5
Stator core axial length	L_{cs} (mm)	50	Rotor core axial length	L_{cr} (mm)	25
Number of slots per pole phase (nspp)		3	Resistance per phase	R_{phase} (Ω)	0.043
Synchronous reactance per phase	X_{phase} (Ω)	0.3897	Efficiency	%	85

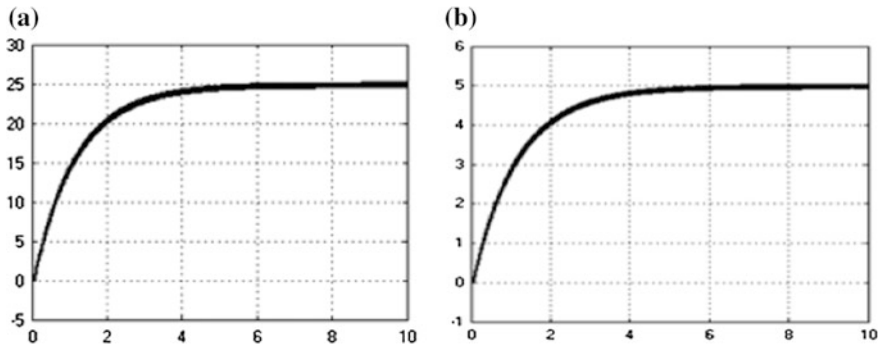

Fig. 8 **a** Output voltage of RE load **b** output current of the RE load at 15 m/s wind speeds

6 Conclusion

The helical two foil turbine with 3600 of twist gives Optimum shaft speed- torque characteristics than that of 900 and 1800 of twist turbines for same dimensions. In the helical 3600 twist turbine the angle of attack is same throughout the length of the blade and the tip speed ratio is near to 1.0, which are defined to be optimum design characteristics. The analysis for 3600 twist turbine with different dimensions by keeping constant radii of 0.5 m, The output torque obtained at shaft torque is proportional to the length of the turbine and wind speed. Variation in L/D ratio also affects the required generator input characteristics. For L/D of 3, best suitable turbine with linear speed and torque characteristics of direct coupled wind energy system. The workbench has the feasibility to test the turbine model at high speeds rather than a manual wind tunnel to estimate the performance. The designed turbine model can archive rated performance at low wind speeds, which suits the requirement of Urban and Rural domestic power requirements.

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