

PERFORMANCE ANALYSIS OF VERTICAL AXIS WIND TURBINE WITH OPTIMISED PITCH ANGLE VARIATION

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Abstract

Wind power generation systems are rapidly growing energy sector due to awareness of green power generation. Vertical axis wind turbine system has potential to improve further for enhance efficiency of energy extraction. Vertical axis wind turbines have several advantages over horizontal axis wind turbine like insensitive of wind direction, easy installation and maintenance, low tip speed ratio etc. Low tip speed ratio cause of high angle of attack, low parasitic drag and less aerodynamics noise production. The main challenges of the vertical axis wind turbine are continuously varying angle of attack, which leads to unsatisfactory self-starting and poor power generation, and ripple in power generation. The problems can be reduced by implementing pitch control with optimized pitch variation due to the variation of azimuth angle and tip speed ratio. In the present study modified, double multiple stem tube (DMST) model has been utilized for obtain the aerodynamic thrust and power output from turbine. The modified DMST model has been obtained by the combination of DMST and BEM model, which can provide better approximation with the consideration of tip loss factor. Optimized pitch variation has been considered to obtain higher power with less power ripple. Matlab Simulink has been used for simulation study of vertical axis wind turbine performance. Comparison of the fixed pitch (FPVAWT) and variable pitch (VPVAWT) system for power extraction has been done with different tip speed ratio.

Keywords: Pitch, wind turbine, multiple steam tube, blade element momentum

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Introduction

Wind power generation systems are growing rapidly globally due to awareness of green power generation. Wind turbine can be classified in two ways, horizontal axis wind turbine and vertical axis wind turbine based on the orientation of the turbine rotor with respect to the wind direction. Comprehensive study of the horizontal axis wind turbine has been done, as it is more promising form in wind industry. Vertical axis wind turbine system has scope to improve further to increase its application. Vertical axis wind turbine has several advantages over horizontal axis wind turbine like insensitive of wind direction, low tip speed ratio, easy installation, maintenance etc (Xu, 2019, Wang and Zhuang, 2017, Bedon *et al.*, 2017, Borg and Collu, 2015, Govind 2017). Low tip speed ratio cause of high angle of attack, low parasitic drag and less aerodynamics noise production (Xu, 2019). Researchers reported effect of blade shape, chord solidity, number of blades, Reynolds number, tip speed ratio, turbulence intensity (Kumbarnuss *et al.*, 2012, Miller *et al.*, 2018, Bachant and Wosnik, 2016, Parker and Leftwich, 2016, Rezaeiha *et al.*, 2018, Ferreira and Geurts, 2014, Rezaeiha *et al.*, 2014, Lam *et al.*, 2018, Sutherland *et al.*, 2012) on the performance of the turbine.

The main challenges of the vertical axis wind turbine are continuously varying angle of attack, which leads to unsatisfactory self-starting and poor power generation, and ripple in power generation may cause of mechanical component damage (Patel *et al.*, 2014) and negative power coefficient cause of dead band at low tip speed ratio (Erfort *et al.*, 2019). The problem can be reduced by implementing pitch control with optimized pitch variation due to the variation of azimuth angle and tip speed ratio. Paraschivoiu *et al.* reported pitch control strategy for two-blade H rotor blade (Bogateanu *et al.*, 2013). Chougule and Nielsen (2014) implemented pitch control system for vertical axis wind turbine, which found enhancement of the efficiency by 12% (Paraschivoiu *et al.*, 2009).

In the present study modified double multiple stem tube (DMST) model has been utilized obtain the aerodynamic thrust and power output from turbine. The modified DMST model has been obtained by the combination of DMST and BEM model, which can provide better approximation with the consideration of tip loss factor. Optimized pitch variation has been considered to obtain higher power with less power ripple. Matlab Simulink has been used for simulation study of vertical axis wind turbine performance. The effect of pitch control and tip speed ratios on power generation has been studied. Optimized pitch angle position with less tip speed ratio has been found suitable operating condition for power generation.

System Description and Modeling

Schematic diagram of a straight blade H rotor vertical axis wind turbine and aerodynamic forces on the turbine blades have been shown in the Figures 1(a) and 1(b) respectively (Chougule and Nielsen, 2014). The Figure 1(a) depicts the construction of a straight blade H rotor vertical axis wind turbine, whereas the Figure 1(b) depicts the velocity diagram and lift-drag force component due to blade aerodynamics for a single blade at different azimuth angle. For a three-blade vertical axis wind turbine due to the air velocity and rotation of the turbine, it can be approximate as wind will interface two blades as upstream and downstream so double multiple stem tube model (DMST) has been considered in the study. Power production by the wind turbine depends on wind, turbine blade rigidity, noise level etc (Chougule and Nielsen, 2014).

Modelling of Upwind Zone

The axial induction factor in the upwind zone can be obtained with respect to the angle of attack, α and azimuth angle θ with the consideration of lift coefficient C_L and coefficient of drag, C_D as,

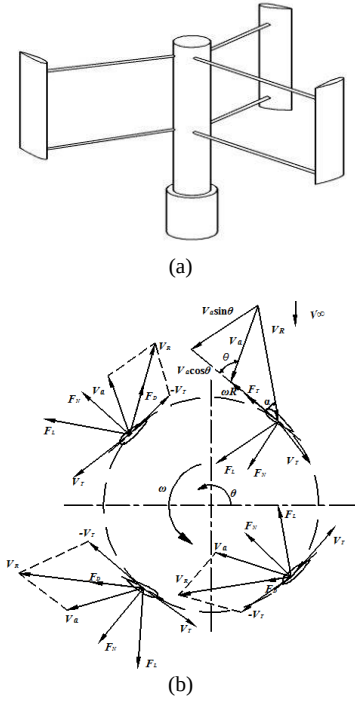


Figure 1. Schematic diagram of (a) straight blade H rotor vertical axis wind turbine (b) aerodynamics force diagram of the turbine blades at some instant (Chougule and Nielsen, 2014)

$$F = \frac{1}{4} \sigma \frac{\sin \theta}{\sin^2 \alpha} (C_L \sin(\theta - \alpha) - C_D \cos(\theta - \alpha)) \quad (1)$$

where the chord solidity, σ is the function of number of blades, chord length, and radius, which can be obtained as,

$$\sigma = \frac{Nc}{2\pi R} \quad (2)$$

with the parameter R , radius of rotor, c is chord length of aerofoil, and N is number of blades. The pitch angle, γ variation can be expressed with azimuthally angle as,

$$\gamma = A_c \sin \theta - \tan^{-1} \left(\frac{\sin \theta}{\cos \theta + \lambda} \right) \quad (3)$$

where, A_c is maximum pitch angle at certain tip speed ratio.

The blade incident angle can be obtained as,

$$\phi_u = \gamma + \alpha_u \quad (4)$$

α_u is angle of attack in upwind zone.

The wind relative velocity can be obtained as,

$$(V_R)_u = \sqrt{(V_u \cos \theta + \omega R)^2 + (V_u \sin \theta)^2} \quad (5)$$

The tangential and normal force coefficient in upwind zone can be represented as,

$$C_{Tu} = C_L \sin \phi_u - C_D \cos \phi_u \quad (6a)$$

$$C_{Nu} = C_L \cos \phi_u - C_D \sin \phi_u \quad (6b)$$

The torque in upwind zone can be calculated as,

$$T_u = \frac{N\Delta\theta}{2\pi} \left(\frac{1}{2} \rho h c R ((V_R)_u)^2 C_{Tu} \right) \quad (7)$$

Modeling of Downwind Zone

The aerodynamic model of the turbine can be obtained in the downwind zone as,

$$F = \frac{a_d}{1 - a_d} \quad (8a)$$

$$a_d = \frac{F}{1 + F} \quad (8b)$$

where, a_d is downwind axial induction factor. The downwind induction velocity of rotor is the average of exit velocity of upwind zone and exit velocity of downwind zone,

$$V_d = \frac{V_e + V'_e}{2} \quad (9)$$

where, V_d is downwind induction velocity of rotor, V_e is exit velocity at upwind zone, and V'_e is exit velocity at downwind zone.

Downwind axial induction factor is defined as ratio of difference between exit velocity at upwind zone and downwind

induction velocity of rotor to free stream wind velocity,

$$a_d = \frac{V_e - V_d}{V_e} \quad (10)$$

The velocity vector on the rotor, it obtained total blade angle in downwind zone,

$$\phi_d = \frac{(1-a_d)(1-2a_u)V_\infty \sin \theta}{(1-a_d)(1-2a_u)V_\infty \cos \theta + \omega R} \quad (11)$$

$$\phi_d = \frac{\sin \theta}{\cos \theta + \lambda/(1-a_d)(1-2a_u)} \quad (12)$$

where, ϕ_d is total blade angle in downwind zone, θ is azimuth angle.

The variable pitch model is used, the blades are rotating in own axis, which the

uniform motion. Variable pitch has been calculated by Equations 6 and 7.

$$\phi_d = \gamma + \alpha_d \quad (13)$$

where, α_d is angle of attack in downwind zone The relative velocity of the blade,

$$(V_R)_d = \sqrt{(V_d \cos \theta + \omega R)^2 + (V_d \sin \theta)^2} \quad (14)$$

The tangential force coefficient and normal force coefficient in upwind zone,

$$C_{T_d} = C_L \sin \phi_d - C_D \cos \phi_d \quad (15a)$$

$$C_{N_d} = C_L \cos \phi_d + C_D \sin \phi_d \quad (15b)$$

The torque in downwind zone:

$$T_d = \frac{N\Delta\theta}{2\pi} \left(\frac{1}{2} \rho h c R ((V_R)_d)^2 C_{T_d} \right) \quad (16)$$

Model validation

Figure 2 has been shown the comparison of the present model with Komass, (2015) (Biadgoa *et al.*, 2013) for 0 to 360° azimuth angle.

The present study has been compared for angle of attack, ratio of lift and drag coefficient, and output torque. The present study has been studied by blue line, whereas the reported work presented by black line. Deviation of the present work and reported has been found marginal within considerable range.

Results and Discussion

The mathematical modeling of vertical axis wind turbine has been done by using modified DMST in MATLAB Simulink environment. In the present study, NACA0018 airfoil set on 0.2m chord length, and turbine radius with 1m have been considered. The height of turbine has been considered as 1 m. Number of blades are considered as 3 and solidity has been calculated with respect to wind velocity and tip speed ratio are 4, 4.5, 5, and 5.5. Span length

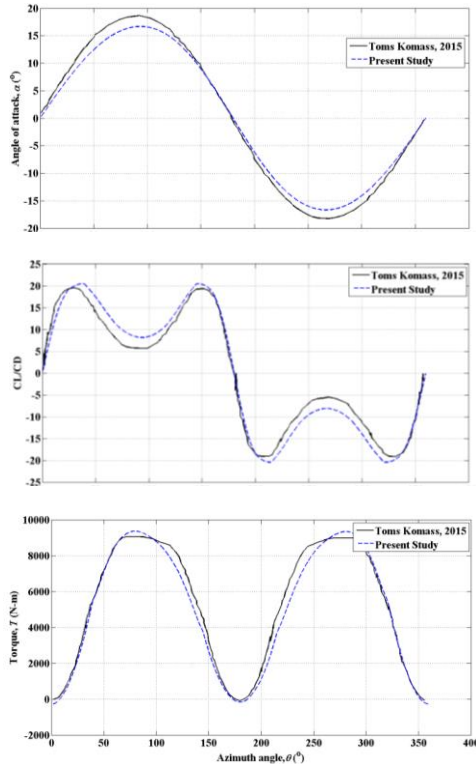


Figure 2. Variation of angle present work with respect to the reported work (Biadgoa *et al.*, 2013)

has been considered as 15 degree to calculate the upstream and downstream of the turbine induction factor a_u and a_d are calculated respectively.

Variation of angle of attack with the variation of azimuth angle has been shown in Figure 3 as blade rotates from 0 to 360 degree. The blue and black colour line represents variation of angle of attack with fixed pitch as well as variable pitch with azimuth angle. Maximum angle of attack occurs at optimum azimuth angle, which is more in upwind zone. In the downwind zone angle of attack is more open as compare to the azimuth angle. As tip speed ratio increases, angle of attack will decrease in both regions. Maximum wind

energy extraction occurs in upwind zone as the rotational speed of rotor increases compare to downwind zone. For a particular wind speed i.e. 5 m/s, the variation of angle of attack has been observed under different tip speed ratios with azimuth angle. At lower tip speed ratio, the angle of attack will be maximum which has ability to extract maximum power due to increases in rotational speed of rotor in upwind zone.

Lift coefficient plays a vital role where lift is generated by the blade and it determines

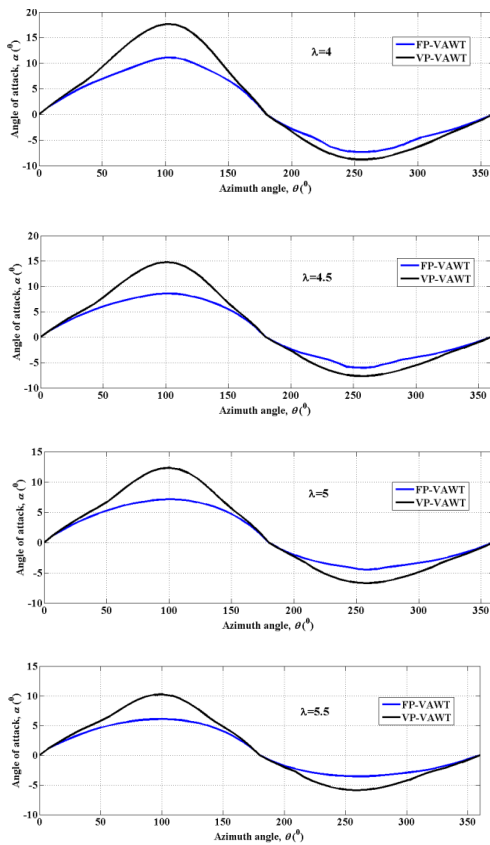


Figure 3. Estimation of angle of attack with variation of azimuth angle at fixed and variable pitch at different tip speed ratio

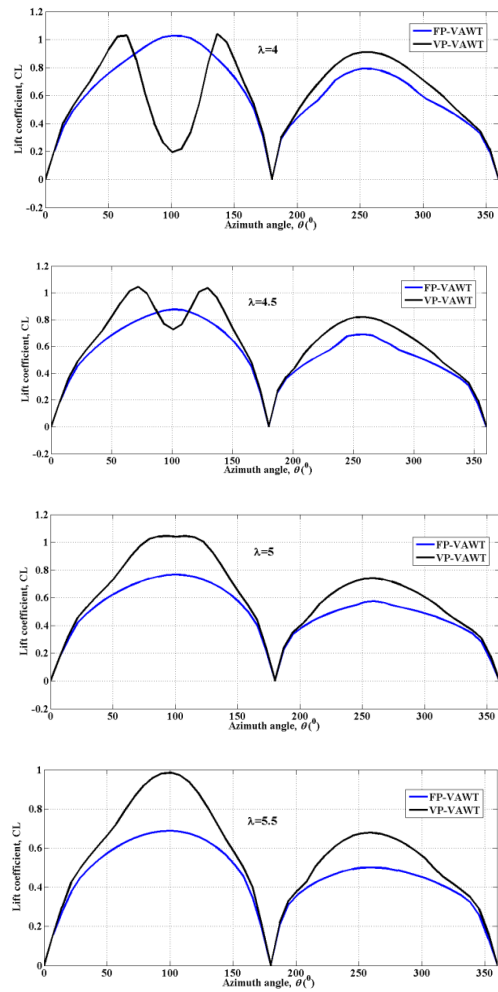


Figure 4. Estimation of lift coefficient with variation of azimuth angle at fixed and variable pitch at different tip speed ratio

the value of tangential force, which is responsible for the rotation of the blade. The variation of lift coefficient due to one complete rotation of the rotor is shown in Figure 4 with blue and black colour lines under different tip speed ratios for a particular wind speed. The blue and black colour line represents variation of lift coefficient with fixed pitch and variable pitch with variation of azimuth pitch angle. For a particular tip speed ratio 4, lift coefficient is varied from 0 to 180 degree at VP-VAWT, lift coefficient is found lower at 90 degrees and higher at 270 degree. When tip speed ratio is increased continuously from 4, then it is observed that at 90 degree lift coefficient is found higher as comparison to the 270 degree. From the figure it can be observed that VP-VAWT is found to be larger as compare to the FP-VAWT.

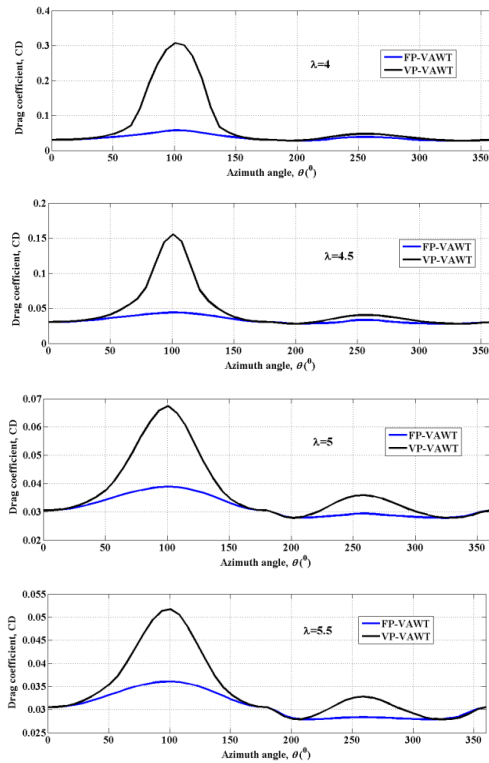


Figure 5. Estimation of drag coefficient with variation of azimuth angle at fixed and variable pitch at different tip speed ratio

The variation of drag coefficient under different tip speed ratios has been shown in Figure 5 with variation of azimuth angle. Drag coefficient is observed optimum at tip speed ratio 4, compare to the other tip speed ratio and same phenomena is observed in downwind zone. When comparison is done between VP-VAWT and FP-VAWT, it has been observed under VP, drag coefficient is found to be higher due to maximum angle of attack. Due to aerodynamics of aerofoil, angle of attack is found to be higher, which results in higher lift and drag coefficient.

Variation of torque with variation of azimuth angle has been shown in Figure 6,

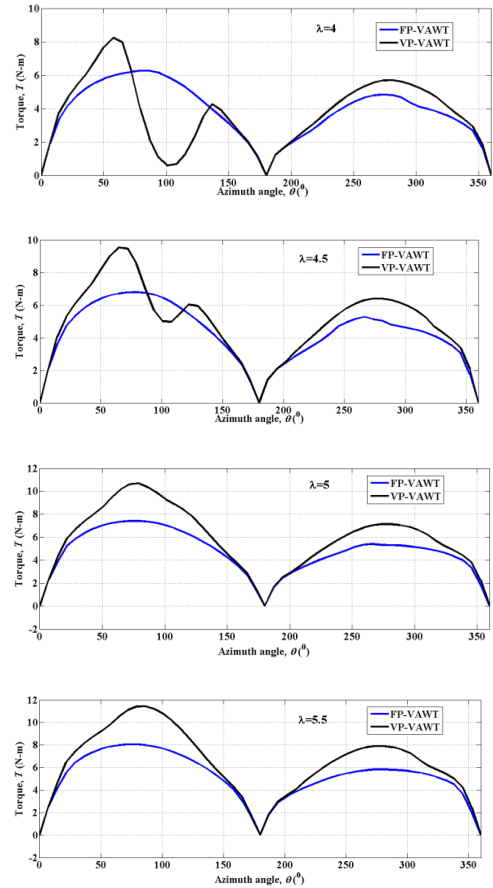


Figure 6. Estimation of torque with variation of azimuth angle at fixed and variable pitch at different tip speed ratio

under different tip speed ratios for a wind speed. Variable pitch increases maximum power extraction power capability at every value of the azimuth angle. At tip speed ratio 4, torque has been obtained higher in the downwind zone as compared to the upwind zone, due to axial induction factor. When comparison has been done at different tip speed ratios for variable and fixed pitch, then it is observed that torque is constant for fixed pitch and fluctuating for variable pitch due to angle of attack.

Conclusions

In the present study, H rotor straight blade vertical axis wind turbine has been considered for analysis with modified DMST model with pitch variation. The present mathematical model has been simulated in Matlab Simulink environment. The present model has been validated with existing result. Performance of the vertical axis wind turbine has been studied with the variation of blade pitch angle and tip speed ratio. It has been found the higher tip speed ratio with pitch angle variation provides better approximation of torque output. In the present study manually optimized pitch angle variation has been done for enhance power output. Application of the soft computing tool for pitch angle variation may provide more better performance.

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