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Performance Analysis of H-Rotor Vertical Axis Wind Turbine

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ABSTRACT

Angle of attack is a well-developed and widely-used approach in modern horizontal axis wind turbines in operation. However, its application in vertical axis wind turbines (VAWTs) is restricted by the ambiguities in its functional mechanism. A generic formulation that uses governing parameters to represent the solution space of the optimal angle of attack control is developed through an in-depth analysis of the relationship between angle of attack and the output torque of VAWTs. Subsequently, a single tube stream model, multiple tube stream model composed of genetic algorithm and MATLAB SIMULINK simulation modules is built to search for angle of attack that can maximize turbine torque. A MATLAB SIMULINK model is used as a performance evaluation tool because of its high computational efficiency. Results show that in a wide range of tip speed ratios (TSRs), the angle of attack and torque coefficient can increase respectively, in two simulated VAWT models with different two stream tube. At stages below the rated TSR, stall induced torque losses are delayed or even avoided by the proposed optimized angle of attack control. At stages beyond the rated TSR, energy extraction in the downwind zone is improved due to increased upwind wake velocity.

Keywords: Wind Turbine, MATLAB, Pitch, Angle of Attack, Lift, Drag.

I. INTRODUCTION

The wind is caused by solar energy and approximately 2% of sun's energy is converted into winds. The surface of earth heats and cools unevenly, creating air to flow from high pressure to low pressure. Wind is renewable sources of energy and it is sustainable for the future generations as wind power is inexhaustible and requires no fuel. Wind turbine power production depends on the interaction between the rotor and the wind. The wind may be considered to be a combination of the mean wind and turbulent fluctuations about that mean flow. Horizontal axis wind turbine designs use aerofoils to transform the kinetic energy in the wind into useful energy. The classical analysis of the wind turbine was originally developed by Betz. Vertical axis wind turbines (VAWTs) may have either drag-driven or lift-driven rotors. The most common drag-driven vertical axis turbine is the Savonius rotor. It has been used for water pumping and other high-torque applications. The argument in favour of Savonius rotor turbines is that they can be relatively inexpensive to build. When vertical axis turbines have been used for electrical power generation they have nearly always used lift-driven rotors. Typically these rotors have had one of two types of configuration: (1) straight blades or (2) curved blades in shape. Thus, power limitation at high winds is accomplished by stalling. The principal advantage of vertical axis rotors is that they do not require any special mechanisms for yawing into wind. By the nature of the aerodynamics of the rotor, the structural loads on each blade vary greatly during each rotation. Such loads contribute to high fatigue damage, and require that the blades and joints themselves have a very long cycle life. the vertical axis turbines do not lend themselves to being supported by a separate, tall tower. This means that a large fraction of the rotor tends be located close to the ground in a region of relatively low wind. Productivity may then be less than that of a horizontal axis machine of equivalent rated power, but on a taller tower. VAWT are more suited to urban areas as they have low noise level and because of the reduced risk associated with their slower rates of rotation. The economic development and viable use of HAWT would in the future be limited, partly due to high stress loads on the large blades. The literature survey of both type of VAWT and HAWT are review as Lin et al., Blade design simulations are performed to study the 150 kW horizontal axis wind turbine. Reynolds-averaged Navier-Stokes equations and RNG k-ε turbulence model are applied for computational simulations to predict turbulent flow. Chen et al., on the mechanism design of the passive pitch control for the small horizontal axis wind turbine (HAWT). The system uses centrifugal force to make Pulley disk driven the pitch angle of the blade. It can achieve the effect of passive pitch control. Otero et al., Gravity loads would also become more significant in future up-scaled machines due to the square-cube law relation between energy capture and rotor mass. We identify the different constructive factors and physical mechanisms which constitute the sources of the cyclic loads on the rotor. Toms Komass et al. Vertical axis wind turbine (VAWT) pitch system simulation model has been designed and verified using the MATLAB SIMULINK tool for blade aerodynamic force simulation. Wang et al., Two counter-rotating straight-bladed VAWTs is used that indicates performance of VAWTs can be greatly improved by properly choosing parameters of the deflector. Zhang et al., Three-bladed H-rotor VAWT model with a geometric scale of 1:100 was used and fixed onto three floating platforms inspired by offshore oil rigs and floating wind turbine prototypes. The three platforms, i.e. single-spar, tri-floater, and hepta-spar, represent a deep draft, strong buoyancy, and a hybrid conceptual model, respectively. Antonio Posa et al., Two values of TSR are investigated here, in order to discuss its influence on the wake structure. Lower TSRs are associated to boundary layer separation closer to the leading edge of the blades and larger rollers, during both upwind and downwind stall. Rolin et al., Small scale vertical-axis wind-turbine (VAWT) is immersed in a boundary-layer in a wind tunnel. Two counter-rotating vortex pairs in the wake induce crosswind motion which reintroduces stream wise momentum into the wake which developed in order to obtain a theoretical basis from which to understand how the aerodynamic behaviour of VAWTs induces crosswind motion consistent with the production of counter-rotating vortex pairs. Naccache et al., In this study of the turbine sensitivity to different incoming wind angles, turbine axes spacing, number of blades, aerofoil profile and blade mounting point. It was found that the D-VAWT has a low sensitivity to TSR, allowing the turbine to operate efficiently for a wide range of TSRs.

Types of wind turbine: The wind turbine is generally classified into two types:

Horizontal Axis Wind Turbine (HAWT): In Horizontal Axis Wind Turbine (HAWTs), the main motor shaft arranged horizontally. The nacelle, rotor shaft, generator and the transmission system are placed at the top of the tower. Horizontal axis wind turbine are being parallel to the ground, the axis of blade rotation is parallel to the wind flow.

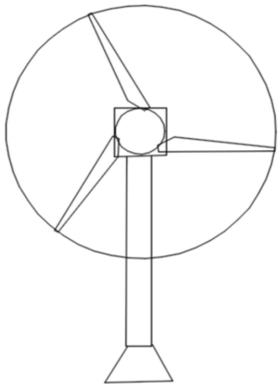


Fig. 1: Schematic diagram of horizontal axis wind turbine.

Vertical axis wind turbine (VAWT): In Vertical axis wind turbine (VAWTs), the main rotor shaft arranged vertically. Vertical axis wind turbines have existed since older days due to they do not take advantage of the higher wind speeds at higher elevations above the ground compare to horizontal axis turbines. A vertical axis machine need not be oriented with respect to wind direction, this is because the shaft is vertical, and the transmission and generator can be mounted at ground level allowing easier servicing and a lighter weight, lower cost tower.

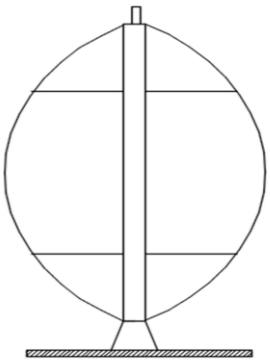


Fig. 2: Schematic diagram of horizontal axis wind turbine.

Airfoil Terminology: A number of terms are used to characterize an airfoil, as shown in Figure 3. It means camber line is the locus of points halfway between the upper and lower surfaces of the airfoil. The most forward and rearward points of the mean camber line are on the leading and trailing edges, respectively. The straight line connecting the leading and trailing edges is the chord line of the airfoil, and the distance from the leading to the trailing edge measured along the chord line of the airfoil. Finally, the angle of attack α is defined as the angle between the relative wind V_R and the chord line.

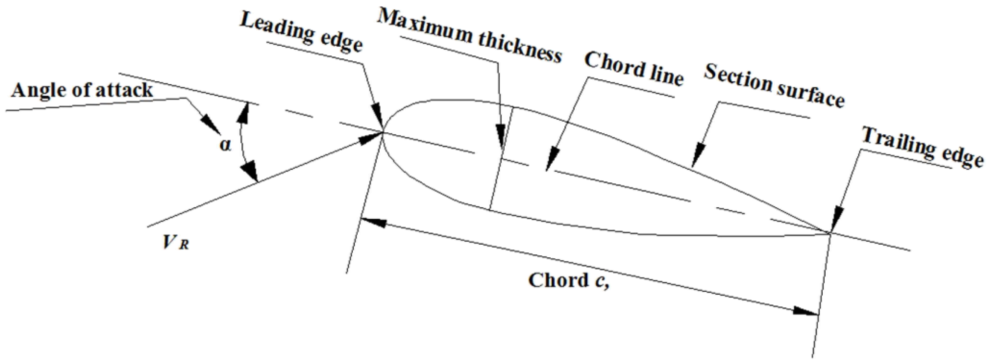


Fig.3: Airfoil nomenclature

Lift force– defined to be perpendicular to direction of the oncoming air flow. The lift force is a consequence of the unequal pressure on the upper and lower airfoil surfaces.

Drag force– defined to be parallel to the direction of the oncoming air flow. The drag force is due both to viscous friction forces at the surface of the airfoil and to unequal pressure on the airfoil surfaces facing toward and away from the oncoming flow.

Pitching moment– defined to be about an axis perpendicular to the airfoil cross- section.

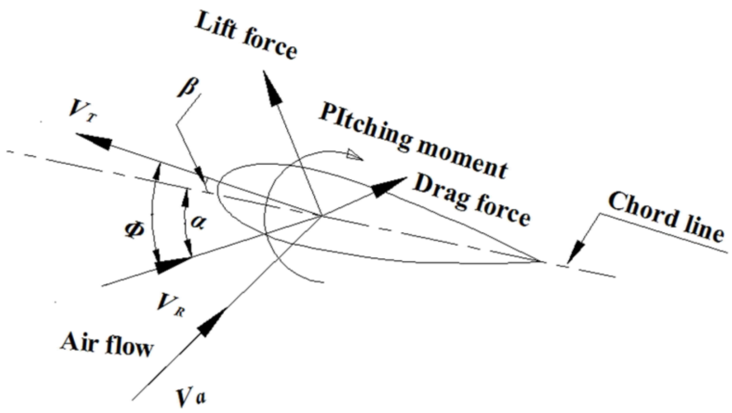


Fig. 4: Forces and moments on an airfoil section

Governing equations of straight blade H rotor type VAWT: *In vertical axis wind turbines, the airfoil is symmetric. The blade is oriented so that the chord line is perpendicular to the radius of the circle of rotation. The radius defining the angular position of the blade makes an angle of* θ *with the wind direction. As the VAWT have a rotational axis perpendicular to the oncoming airflow, the have aerodynamics involved are more complicated than of the more conventional HAWT.*

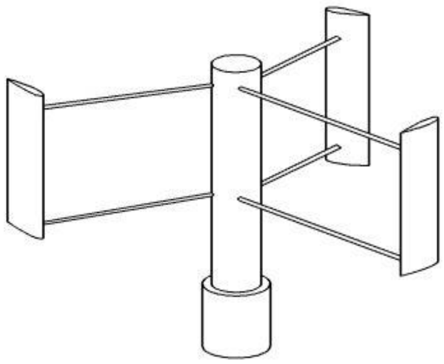


Fig.: Straight blade H rotor type VAWT

If the straight blade H rotor type VAWT is represented in a two dimensional way as shown in figure

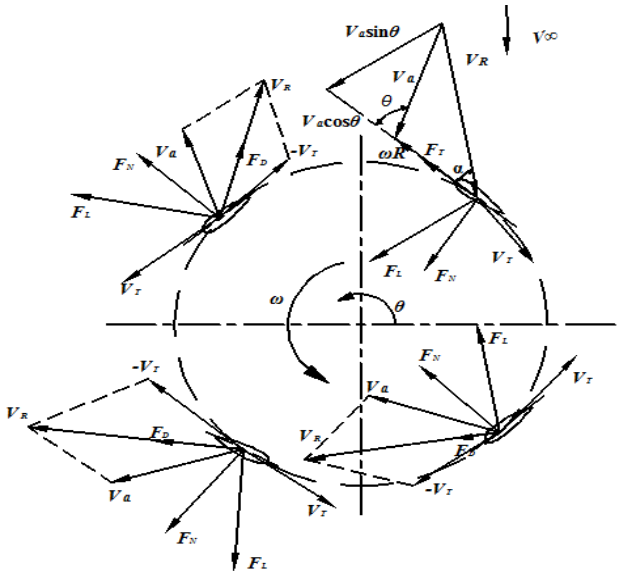


Fig: VAWT flow velocities and blade

When the wind energy goes into the wind turbine blade the velocity is calculated in accordance with the angle of the azimuth and the turbine rotation speed and wind speed.

$$V_T = V_a \cos\theta + \omega.R$$

$$V_A = \sin\theta.V_a$$

Where, V_T is the tangential linear velocity, V_A is the radial force, V_a is the induced velocity through the rotor, ω is the rotational velocity, R is the radius of the turbine, and θ is the azimuth angle.

By Pythagoras's Theorem, is:

$$V_R{}^2 = V_T^2 + V_A^2$$

$$V_R = \sqrt{(V_a \cos\theta + \omega.R)^2 + (V_a \sin\theta)^2}$$

Where, V_R is the relative velocity to the blade element (m/sec) and V_a is the induced velocity through the rotor.

The relative velocity can be written in non-dimensional form using free stream velocity:

$$\frac{V_R}{V_\infty} = \sqrt{\left(\frac{V_a}{V_\infty}\cos\theta + \frac{\omega.R}{V_\infty}\right)^2 + \left(\frac{V_a}{V_\infty}\sin\theta\right)^2}$$

Since induced velocity through the rotor $V_a = V_\infty(1 - a)$ and $\lambda = \frac{\omega R}{V_\infty}$ is the tip speed ratio.

$$\frac{V_R}{V_\infty} = \sqrt{((1-a)\cos\theta + \lambda)^2 + ((1-a)\sin\theta)^2}$$

Since the chord is perpendicular to the radius of the circle, the angle of attack is:

$$\alpha = \tan^{-1}\left(\frac{V_a\sin\theta}{\lambda + V_a\cos\theta}\right)$$

The normal force coefficients and tangential force coefficients can be expressed as:

$$C_N = C_L\cos\alpha + C_D\sin\alpha$$

$$C_T = C_L\sin\alpha - C_D\cos\alpha$$

Where, C_L is the lift coefficient and C_D is the drag coefficient for angle of attack α

Then the normal and tangential forces for single blade at a single azimuthal location are:

$$F_N = \frac{1}{2}\rho V_R^2(hc)C_N$$

$$F_T = \frac{1}{2}\rho V_R^2(hc)C_T$$

Where, h is the blade height, c is the blade chord length, F_N is the normal force and F_T is the tangential force.

The instantaneous torque or the torque by a single blade at a single azimuthal location is:

$$T_i = F_T R$$

Where, T_i is the torque, R is the radius of the turbine and F_T is the tangential force.

Results and discussions: VAWT blade torque simulation subsystem receives all inputs from the set point by the MATLAB

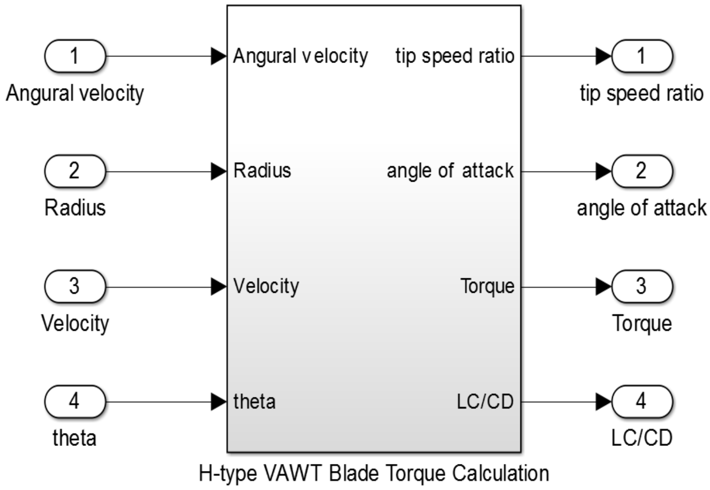


Fig: SIMULINK simulation system

Angle of attack in the period of rotation from 0° –180° is symmetrical to the curve in the period 181° –360°. Angle of attack of the aerofoil is changing at any time due to the rotation of the blades, from 0° to 90° it is first increased and from 90° to 180° graph decreases, similarly from 180° to 270° and from 270° to 360°.

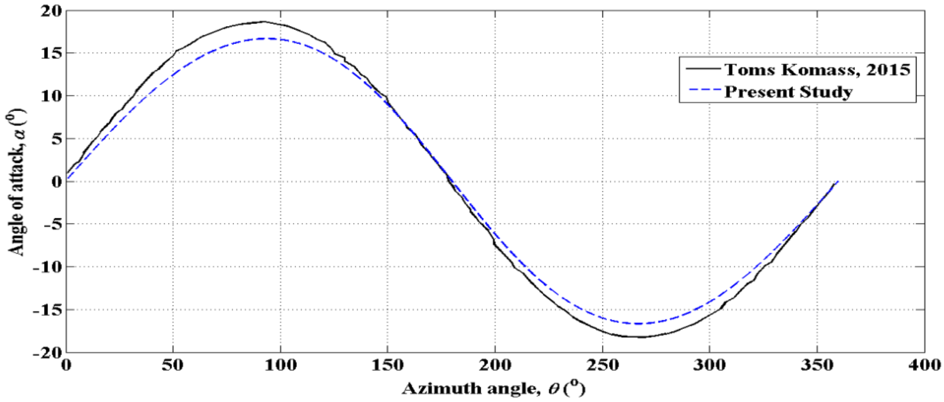


Fig.: Angle of attack as the function of azimuth angle

Lift and drag coefficient values are taken from NACA0018 blade profile. Angle of attack varies from -20 < α > 20 besides this flow is laminar Re = 50000, when this data is given as the input value to the MATLAB SIMULINK and it is also compared from Toms Komass, (2015).

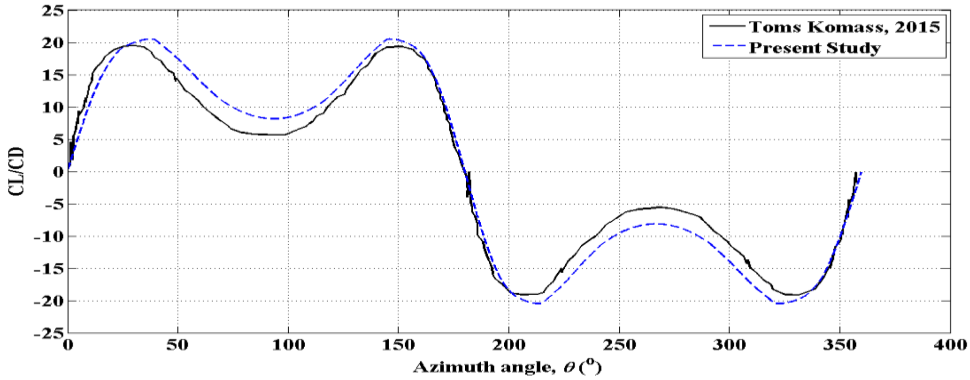


Fig.: CL/CD as the function of Azimuth angle

When wind velocity, radius, azimuth angle and geometric parameters is given as input parameter to the MATLAM SIMULINK than torque is obtain as output and variation of torque is shown in the following graph

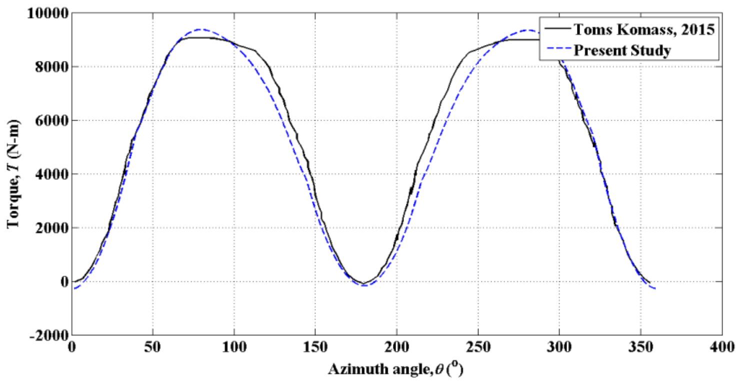


Fig.: Blade produced torque as the function of azimuth angle

It is validated from Toms Komass, (2015) in the first quadrant torque increases, because lift force increases and in the second quadrant torque decreases because drag force increase. In the same way, torque in the third quadrant increases and in the fourth quadrant torque decreases.

For single blade azimuth angle is varied from 0° to 360° by keeping all parameter as constant and varying tip speed ratio and blade rotates counter clockwise direction and for each angular velocity is varied, free stream velocity is fixed and data is simulated in the MATLAB, torque is obtain which is explained by the following graph.

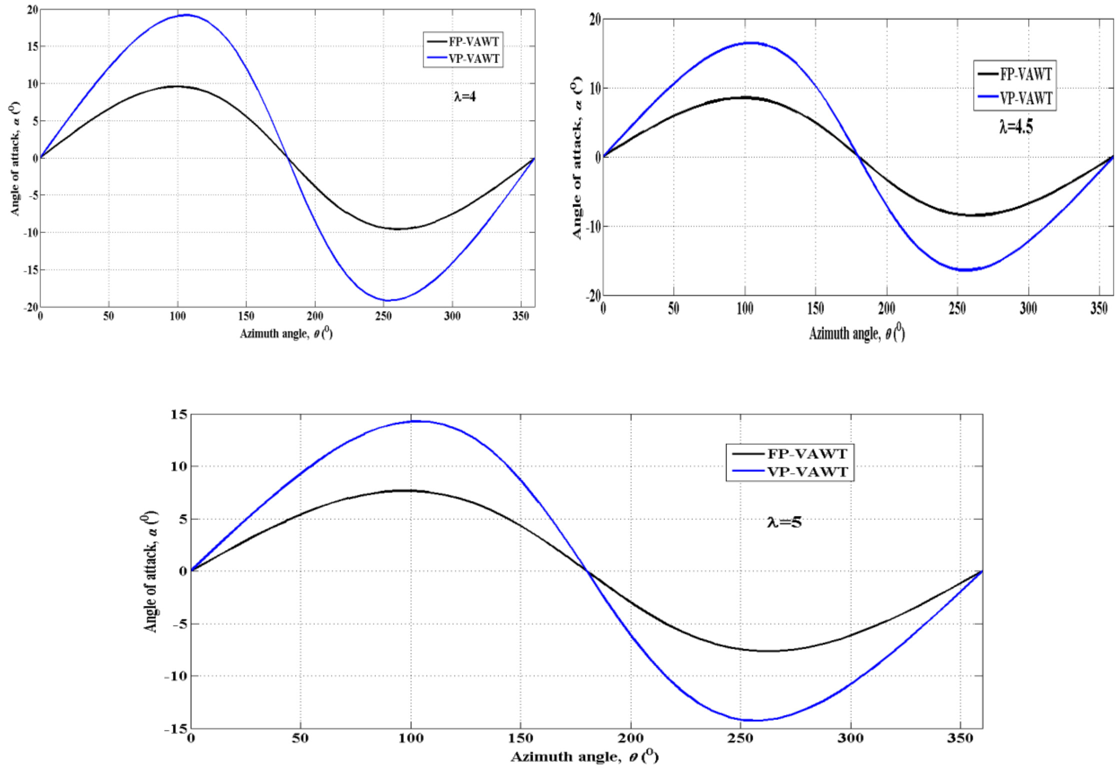
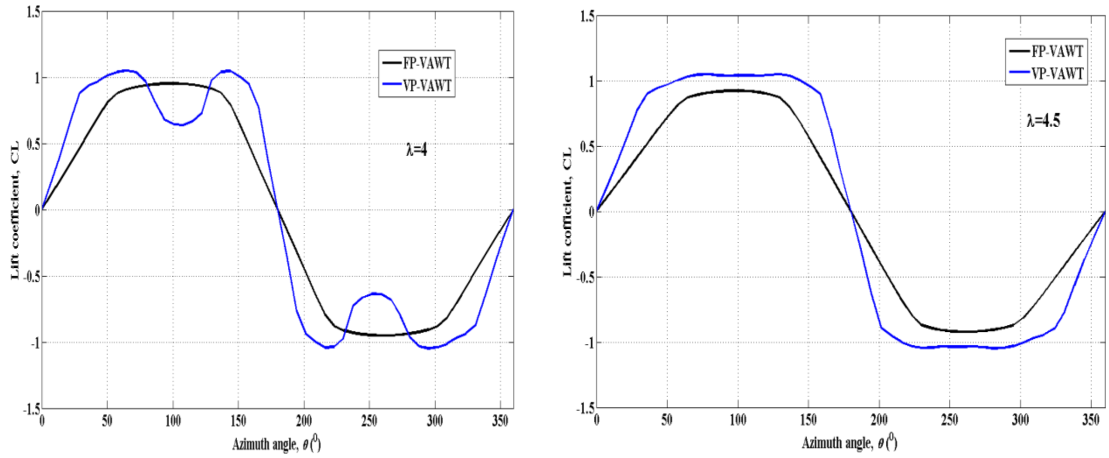


Fig.: Variation of angle of attack



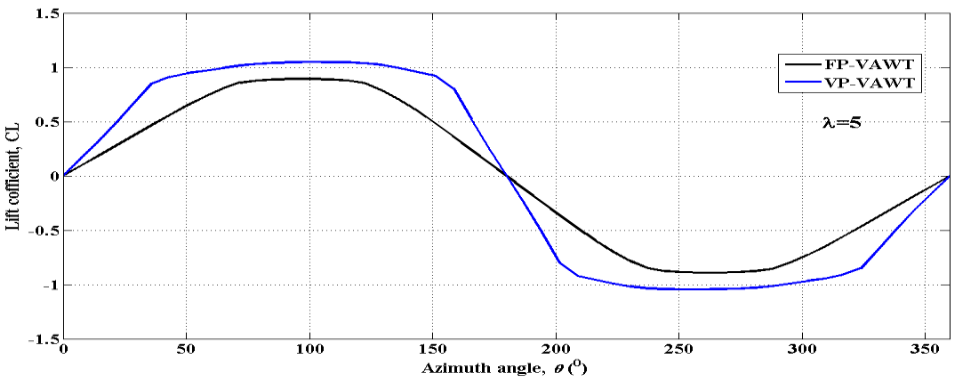


Fig.: Variation of lift coefficient

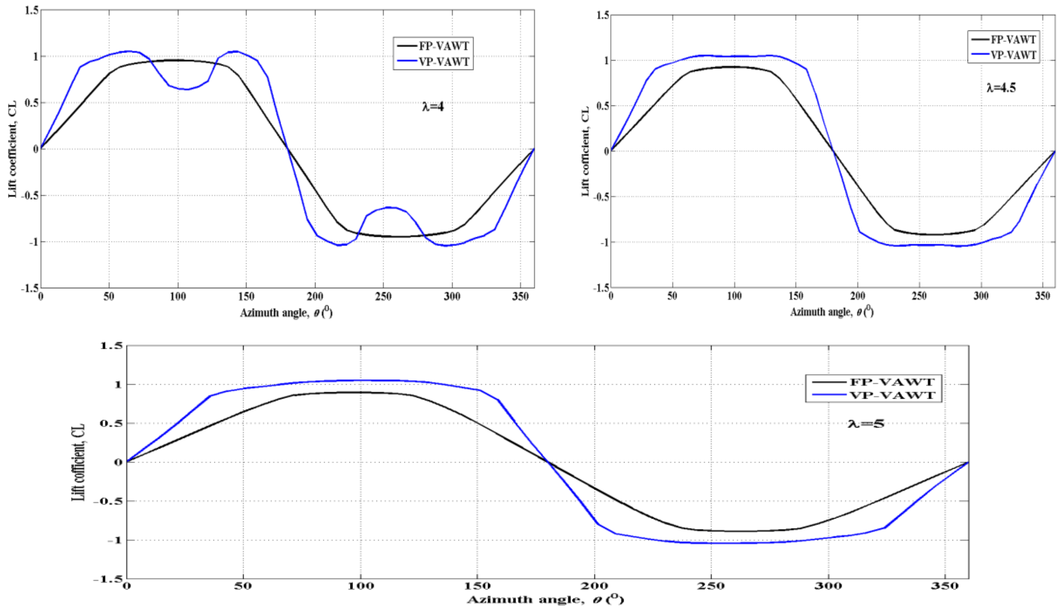
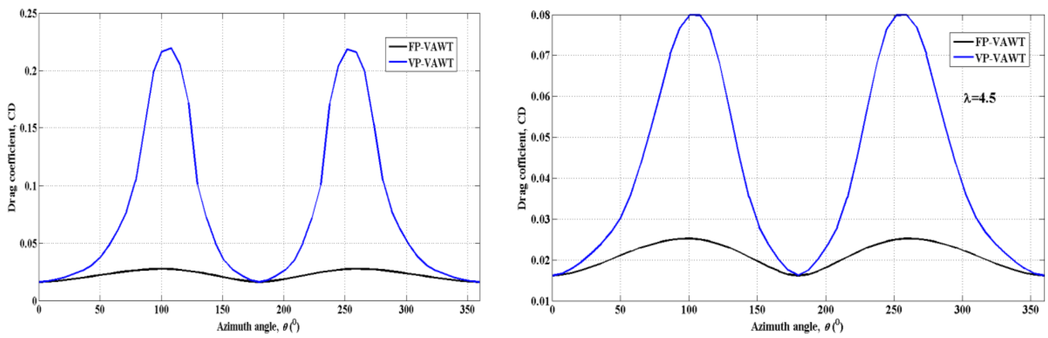


Fig.: Variation of lift coefficient



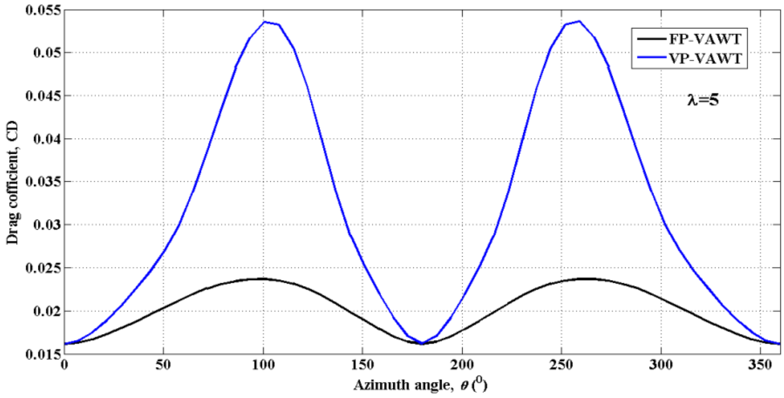


Fig.: Variation of drag coefficient

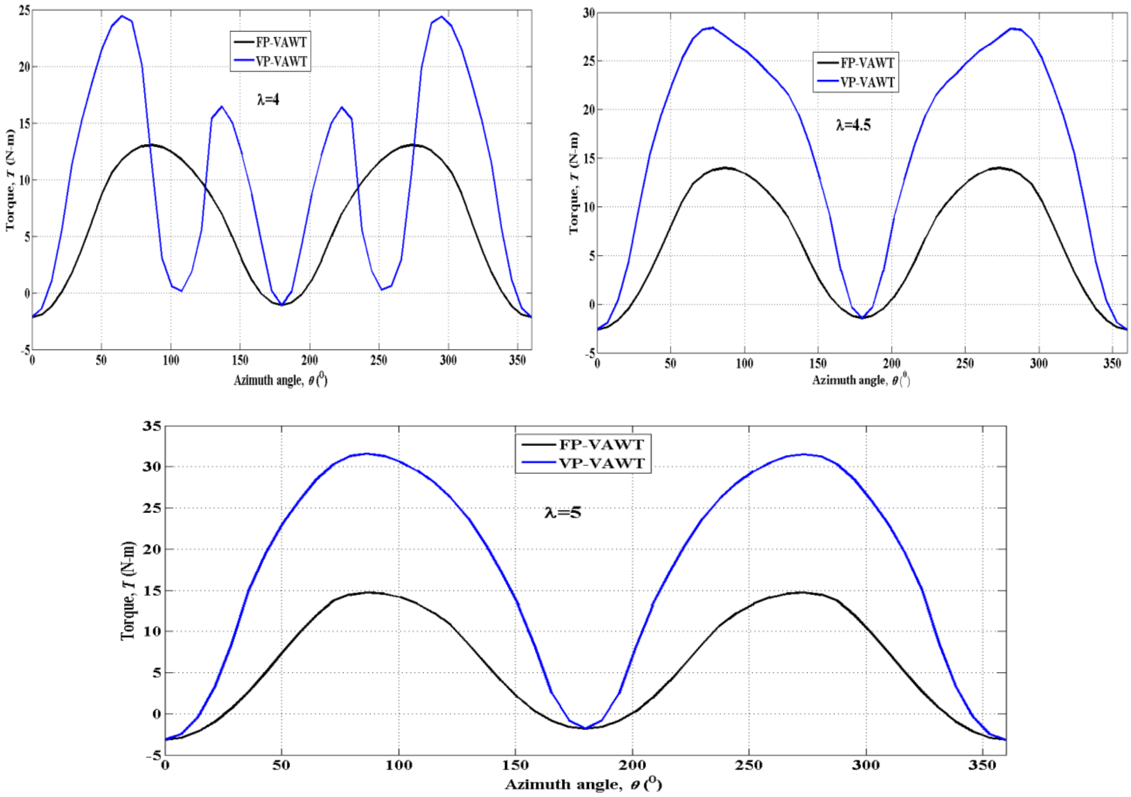


Fig.: Variation of torque

For double blade azimuth angle is varied from 0° to 360° by keeping all parameter as constant and varying tip speed ratio, and blade rotates counter clockwise direction and for each angular velocity is varied, free stream velocity is fixed and data is simulated in the MATLAB, torque is obtain which is explained by the following graph.

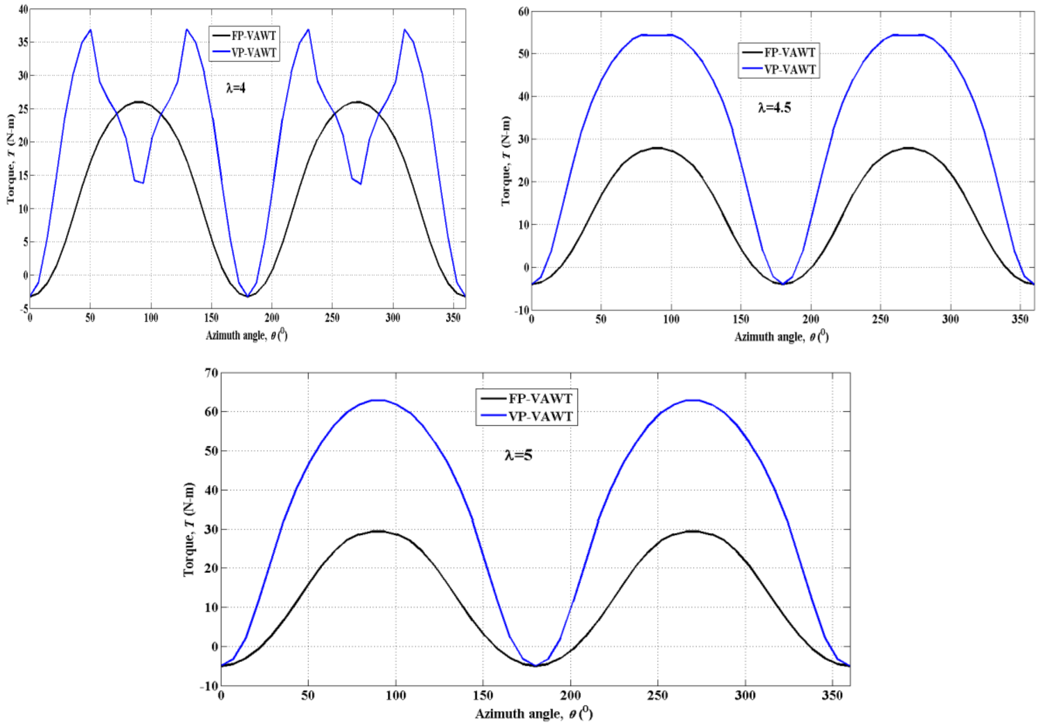
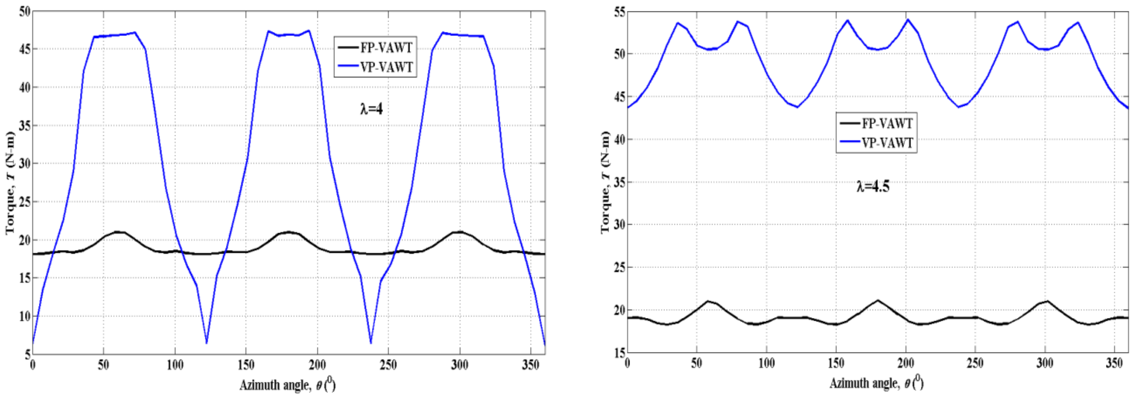


Fig.: Torque with variation of azimuth angle at different tip speed ratio at constant free stream velocity and double blades.

For three blade azimuth angle is varied from 0° to 360° by keeping all parameter as constant and varying tip speed ratio, and blade rotates counter clockwise direction and for each angular velocity is varied, free stream velocity is fixed and data is simulated in the MATLAB, torque is obtain which is explained by the following graph.



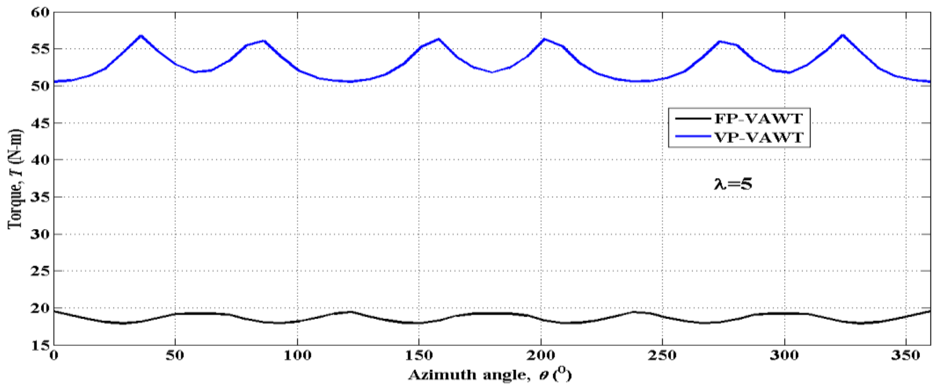


Fig.: Torque with variation of azimuth angle at different tip speed ratio at constant free stream velocity and three blades.

Hence, we can say that if number of blades is increased then torque increase.

II. CONCLUSION

From above graphs following conclusions can be below as:

- In two-dimensional simulation method, the prediction on the performance of H-type vertical axis wind turbine is feasible. the process of rotor rotation, the change of angle of attack range should be as large as possible that requires high degree of tip speed ratio.
- Negative torque creates the problem of self-starting, low tip speed ratio and more number of blades.
- Increase number of blades and tip speed ratio results higher torque, because increase in tip speed ratio and more number of blades results increase in angular velocity.
- As compare to single stream tube model more torque is obtain in multiple stream tube because different induction velocity produced.

III. FUTURE SCOPE

The simulation system algorithms can be adjusted to any turbine dimensions and turbine blade profile. The simulation program is flexible and can be used for future VAWT development simulation systems.

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