VERTICAL WIND TURBINE WITH VARIABLE BLADE ANGULAR POSITION

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Abstract. *Wind energy is being used today by most developed countries to replace the consumption of fossil fuels in electricity production, in order to reduce dependence on those types of nonrenewable resources, and also greatly reduce proportion of environmental pollution. Harnessing wind power is not new, but now studies are conducted to improve the efficiency of wind turbines. In this case is made a study of a vertical axis wind turbine (H- Darreius or Giromill) with four symmetrical blades, using the single streamtube model with Glauert´s blade element theory and one fixed wind direction as energy source. In order to optimize its efficiency angles of attack of each vertical blade are changed to amplify the effect of the aerodynamical force due to the wind, generating more torque on the turbine. The angular position of the blade shall accordingly depend on the freestream velocity and the angular speed of system. Several simulations are made using different values showing the dynamical behavior of the turbine.*

Keywords*: Blade angle of attack, Vertical Axis Wind Turbine, Wind energy.*

1. INTRODUCTION

Due to necessity of reducing pollution emissions, today wind turbine's manufacturers make great efforts to implement mechanisms to reduce the price further and to make wind energy more competitive with other production methods, besides developing mechanisms to improve their efficiency (Hansen, 2008). Blades of VAWT may be of uniform section and untwisted making them relatively easy to fabricate or extrude, unlike the blades of horizontal axis wind turbine (HAWT), which should be twisted and tapered for optimum performance. Furthermore, they produce less noise than the HAWT with the same power coefficient at normal operating speed and almost the less costs of maintenance due the blades are located at the ground (Islam, Ting and Fartaj, 2007).

In this case, it was studied the dynamics of a H- Darreius wind turbine, with four symmetrical blades, as shown in Fig.(1), finding the angular position (or angle of attack) of each blade where it generates the most torque possible for the turbine rotation. Turbine is simulated with no load and a constant load, representing the generator torque acting in the opposite direction to the rotation of the turbine, considering the single streamtube model where induced wind velocity is the same for all blades (Templin, 1974), and using an algorithm previously developed by the authors.

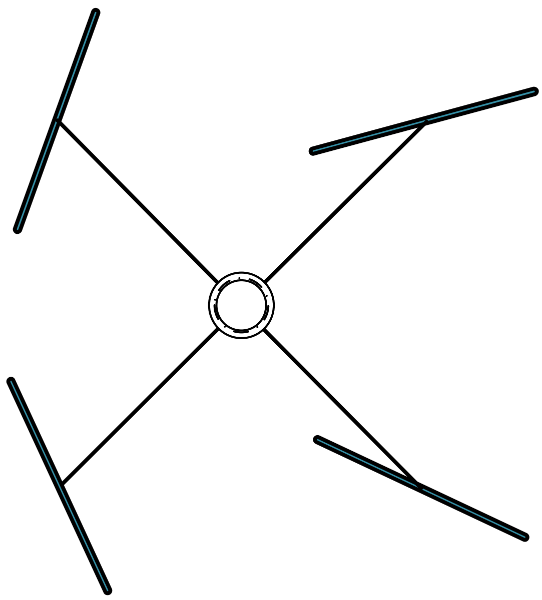

Figure 1. H- Darreius Turbine layout

2. BLADE ANGULAR POSITION FOR VAWT

To determine the optimal angle of the blade, it should take into consideration the aerodynamic forces impinging on the blade separately proposed by Glauert´s blade element theory (Glauert, 1948), which are divided into drag and lift force, depending on the magnitude and direction of the turbine velocity, as well as the direction and magnitude of wind velocity (source). The torque in each blade is defined by the product between the turbine radio and the sum of the components of aerodynamic forces. Total torque can be computed as the sum of all blade torques, if it is considered that aerodynamics forces in each blade are independent of the other ones.

2.1. Simplified dynamic equations for VAWT

Figure 2 shows the relation between the velocities and forces generated by wind velocity.

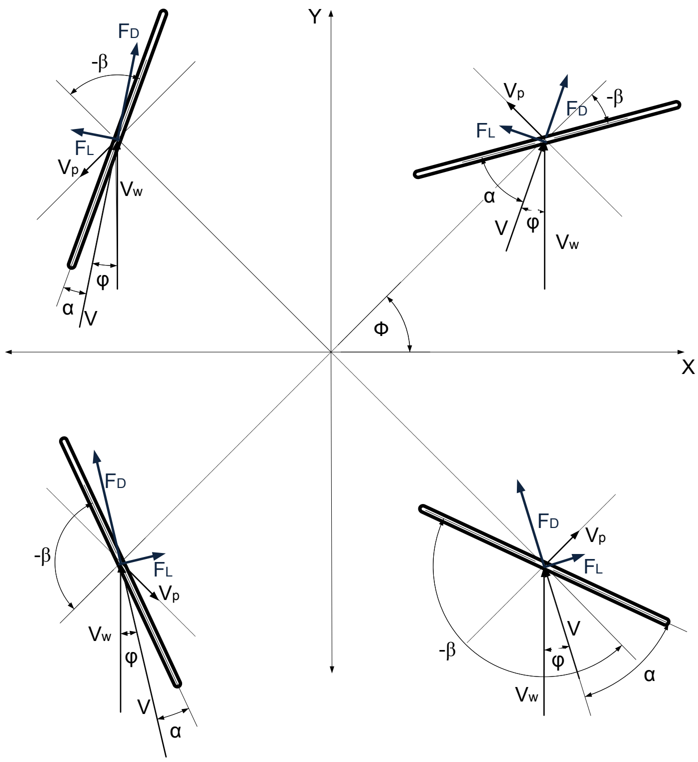

Figure 2. Diagram of speeds and forces in the turbine

Where F_D, F_L, C_D and C_L are the drag and lift forces and coefficients respectively, V is the relative speed between the wind source speed V_W and blade speed V_P, φ is the angle between relative speed and wind speed, β is the position angle of the blade (the value to be optimized) and α is the attack.

The relative speed is expressed as:

$$[V] = [V_w] - [V_p] \tag{1}$$

Using trigonometric relations, the magnitude of relative speed is:

$$|V| = \begin{cases} \sqrt{\left(|V_w| - |V_p|\cos(\phi)\right)^2 + \left(|V_p|\sin(\phi)\right)^2} & 0 \le \phi < \pi/2 \\ \sqrt{\left(|V_w| + |V_p|\sin(\phi - \pi/2)\right)^2 + \left(|V_p|\cos(\phi - \pi/2)\right)^2} & \pi/2 \le \phi < \pi \\ \sqrt{\left(|V_w| + |V_p|\sin(3\pi/2 - \phi)\right)^2 + \left(|V_p|\cos(3\pi/2 - \phi)\right)^2} & \pi \le \phi < 3\pi/2 \\ \sqrt{\left(|V_w| - |V_p|\cos(2\pi - \phi)\right)^2 + \left(|V_p|\sin(2\pi - \phi)\right)^2} & 3\pi/2 \le \phi < 2\pi \end{cases} \tag{2}$$

Angle φ can be calculated as:

$$\varphi = \begin{cases} \pi/2 - a\sin\left(\dfrac{|V_p|\sin(\phi)}{|V|}\right) & 0 \le \phi < \pi/2 \\ \pi - \phi - a\sin\left(\dfrac{|V_w|\sin(\phi)}{|V|}\right) & \pi/2 \le \phi < \pi \\ \phi - \pi - a\sin\left(\dfrac{|V_w|\sin(2\pi - \phi)}{|V|}\right) & \pi \le \phi < 3\pi/2 \\ a\sin\left(\dfrac{|V_w|\sin(2\pi - \phi)}{|V|}\right) & 3\pi/2 \le \phi < 2\pi \end{cases} \tag{3}$$

And finally, the attack angle is determined as:

$$\alpha = \begin{cases} \beta + \varphi - \phi & 0 \le \phi < \pi/2 \\ \pi/2 + \beta - \phi - \varphi & \pi/2 \le \phi < \pi \\ \phi - \pi/2 - \varphi - \beta & \pi \le \phi < 3\pi/2 \\ \phi - \varphi - \beta - \pi/2 & 3\pi/2 \le \phi < 2\pi \end{cases} \tag{4}$$

For the computing (algorithm), the variable β was designated as a vector (set of integers form zero to 180), then the angle of attack α is designated also as a vector.

2.2. Lift and drag forces

The lift and drag forces are expressed as:

$$F_L = \frac{1}{2} C_L \rho A |V^2| \tag{5}$$

$$F_D = \frac{1}{2} C_D \rho A |V^2| \tag{6}$$

Where F_D and F_L are lift and drag force respectively. C_D and C_L are lift and drag coefficient (obtained experimentally), ρ is the mass density of flow (air). A is the projected area of the airfoil, and V is the velocity of the relative flow.

Lift and Drag coefficients were obtained experimentally for a flat blade where the fluid was water (Van, 2011; Caplan and Gardner, 2007). These coefficients were applied in the turbine analysis, only changing the density value of the fluid (in this case air).

The function of lift and drag coefficient as function of angle of attack are expressed as:

$$C_D = 2K_D \sin^2(\alpha) + C_f \tag{7}$$

$$C_L = K_L \sin(2\alpha) \tag{8}$$

Where K_D and K_L are experimental coefficients, and depend of Reynolds number, viscosity of fluid, etc. In this case, the value for simulations was 1 and 0.35 respectively (Van, 2011). C_f is the effective zero-lift drag value, in this case it is 0.03.

Figure 3 shows the function graphics between the drag and lift coefficients as a function of angle of attack.

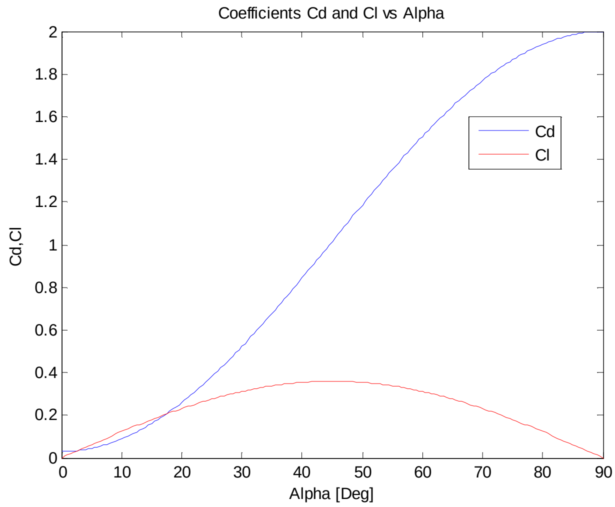

Figure 3. Coefficients of drag and lift as function of angle of attack

With the coefficients computed, it is possible to calculate the lift and drag forces, then the torque for each blade. It is expressed as:

$$T = \begin{cases} R(F_L \cos(\phi + \varphi - \pi/2) - F_D \sin(\phi + \varphi - \pi/2)) - T_G & 0 \le \phi < \pi/2 \\ R(F_L \sin(\pi - \phi - \varphi) - F_D \cos(\pi - \phi - \varphi)) - T_G & \pi/2 \le \phi < \pi \\ R(F_L \sin(\phi - \pi - \varphi) - F_D \cos(\phi - \pi - \varphi)) - T_G & \pi \le \phi < 3\pi/2 \\ R(F_L \cos(\phi - 3\pi/2 - \varphi) - F_D \cos(\phi - 3\pi/2 - \varphi)) - T_G & 3\pi/2 \le \phi < 2\pi \end{cases} \tag{9}$$

Where R is the distance between the center of the turbine and the center of the blade (turbine radio), and T_G is the torque made by the load, and it is in the opposite direction.

Using classical momentum equations, it is valid that:

$$W = W_0 + \ddot{\phi}\Delta t \tag{10}$$

$$\phi = \phi_0 + W_0\Delta t + \frac{\ddot{\phi}\Delta t^2}{2} \tag{11}$$

Where Δt is the differential time, in this case 0.1 W_0 and ϕ_0 , the angular speed and initial position.

Knowing that torque is the product of the moment of inertia *I* (in this case it will be considered in only one axis) and angular acceleration Eq. (12), it is possible substitute into a new equation:

$$T = I\ddot{\phi} \tag{12}$$

Thus:

$$\phi = \phi_0 + W_0\Delta t + \frac{T\Delta t^2}{2I} \tag{13}$$

2.3. Simulation of turbine without wind speed source

Using the values in Tab.1, there was implemented an algorithm (developed by authors in MATLAB® language) to simulate and compute the torques, the optimal angles, the velocity, etc. Algorithm computes in each differential time Δt the torque of each blade using the angular position β as a set of integers from zero to 180 (vector), and choosing the value in that set where the torque is the highest, then adds the maximal torque of each blade to obtain the total torque value. Using classical equations Eq(10), Eq(11) and Eq(13), it is computed the new velocity, angle position of turbine and of each blade.

Table 1. Experimental values for simulation of turbine without load.

Proprieties and boundary conditions	VALUES
Vw (m/s)	0.5
Δt (s)	0.1
W_o (rad/s)	0.25
$Ø_0$(rad)	0
I(Kg/m²)	0.3
A(m^2)	0.06
R(m)	0.5
T_G (Nm)	0

Note: Small prototype projected by author. Laboratory of Acoustic and Vibrations of Federal University of Rio de Janeiro. 2010.

Due to the aerodynamic drag force exists even though the angle of attack is zero, the turbine will tend to stop as can be seen in Fig. 4, where is appreciated that linear speed decreases to zero.

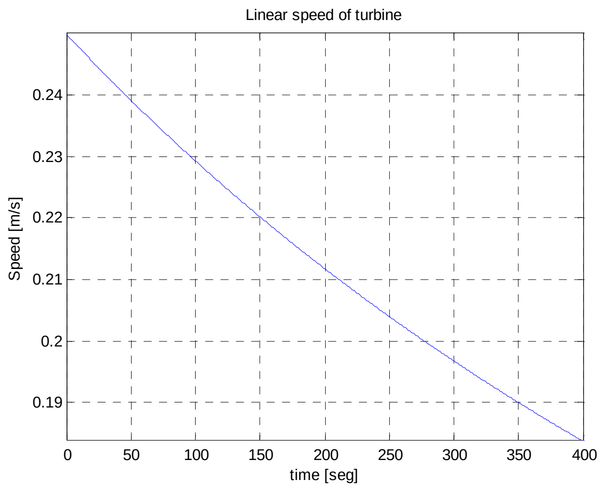

Figure 4. VAWT Linear speed with V_w=0 (m/s)

Was performed a simulation with the parameters of Tab. 1 except the speed of the wind turbine (*Vw*= 0). In this case, It is wanted to see how the behavior of the blades was if the wind speed was zero and take an initial speed turbine.

Fig. 5 shows the layout of the turbine blades fully rotated 90 degrees in order to exert the least possible drag force to stop the turbine.

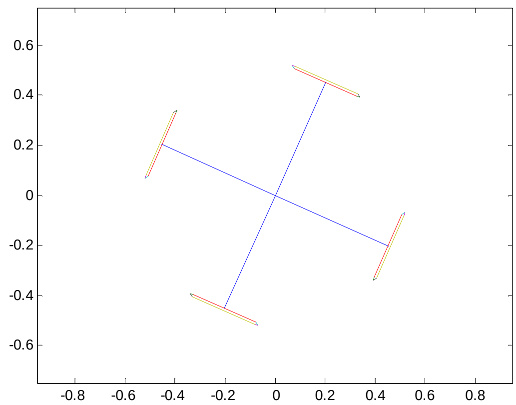

Figure 5. Layout of turbine with V_w=0 (rad. /s)

2.4. Simulation of turbine without load

Using the parameters of the Tab. 1, algorithm computes the optimal angle β for each blade as function of time (in each differential time Δt, algorithm computes the optimal β), where it produces the highest torque possible due to aerodynamic forces.

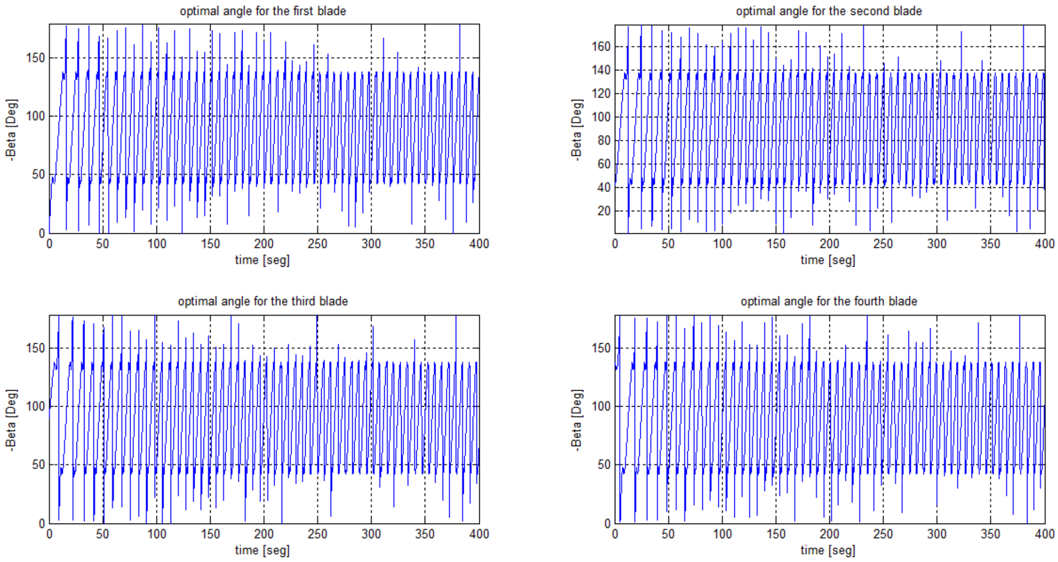

Figure 6. VAWT optimal angles without load

With optimal angles computed, algorithm simulates the linear speed of the turbine, as shown in Fig. 7. Note that the velocity tends to converge to the same wind speed, but reaching this speed, the turbine loses torque, and thus the possible power generated will be zero (Obviously, the system is without load).

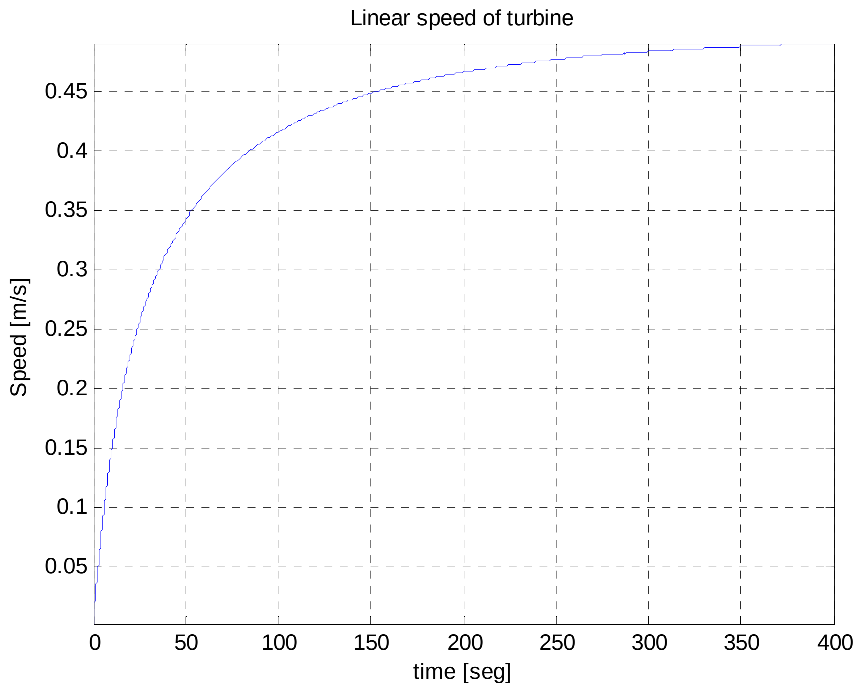

Figure 7. VAWT linear speed without load

Due to speed of the turbine without charge tends to reach the wind speed, the rate of change of the blades also increases, as shown in Fig. 8. Depending on the magnitude of the relative velocity (that it is the vector difference between the wind source velocity and turbine velocity), the optimum angle of each blade will vary.

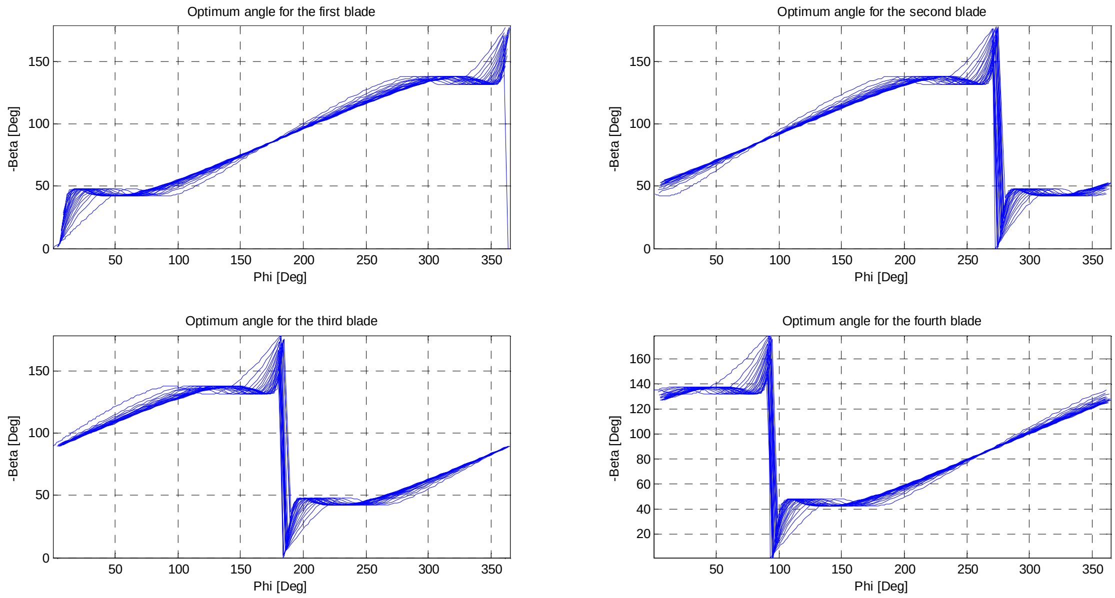

Figure 8. VAWT optimal angles without load

Fig. 9 shows the torque generated as function of time. It can see that in some instances the torques on the blades are negative, because they are moving in the opposite direction of the wind speed, and there is a force minimum drag, even though the angle of attack of zero. Because in this simulation there is not load, the total turbine torque converges to zero when the turbine reaches the wind source speed (Fig. 7). All torques are computed with optimal angle position values of each blade.

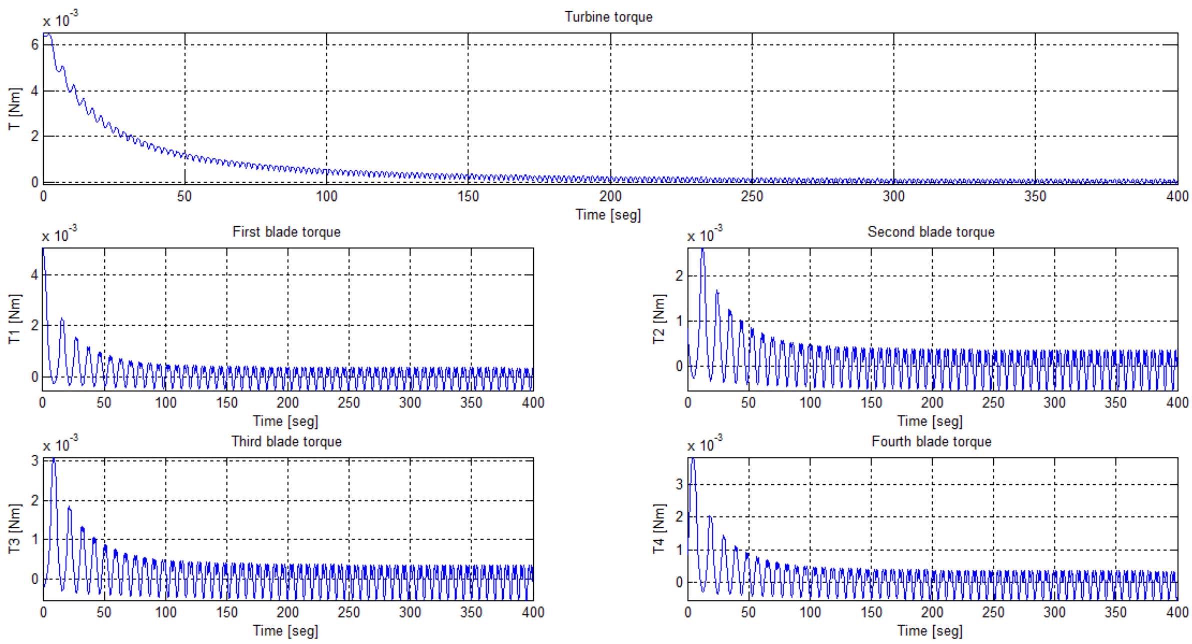

Figure 9. VAWT torques without load

Fig. 10 represents the layout of the turbine when gives its first round. The first blade is quasi perpendicular to the wind flow direction, and the third one is parallel to the same flow. It is reasonable if it is thought that the highest force approached for a plane blade will be when the relative velocity of fluid is perpendicular to the blade cord, and the lowest force will be when the relative velocity is parallel with the blade cord.

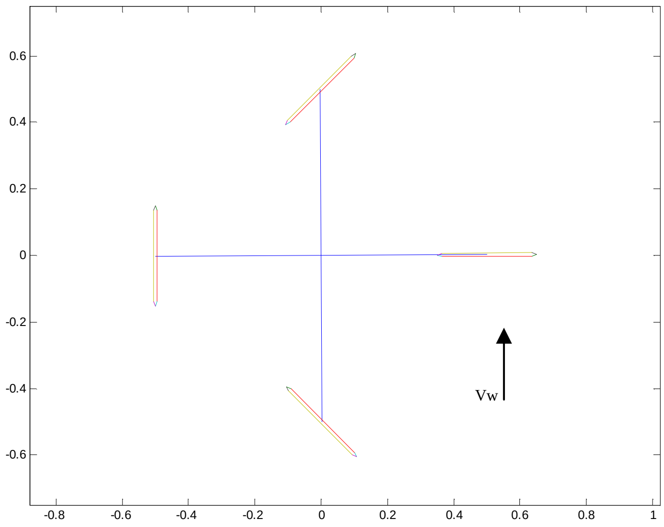

Figure 10. Layout of turbine without load

2.5. Simulation of turbine with constant load

It was evaluated the dynamics of the turbine with same parameters of Tab. 1, but now with a constant load, 0.01 (Nm). Fig. 11 shows the optimal angles for the turbine load. Comparing it with Fig. 6, behaviors of the optimal angles tend to keep in the same period.

For all simulations, algorithm computes for each value of integer set β, the torque produced, choosing the highest one(by each blade), meaning that it value will be the 'optimal angle' (Optimal angle refers to the values β where the blade approaches the highest torque possible due to the aerodynamic forces), for each differential time Δt.

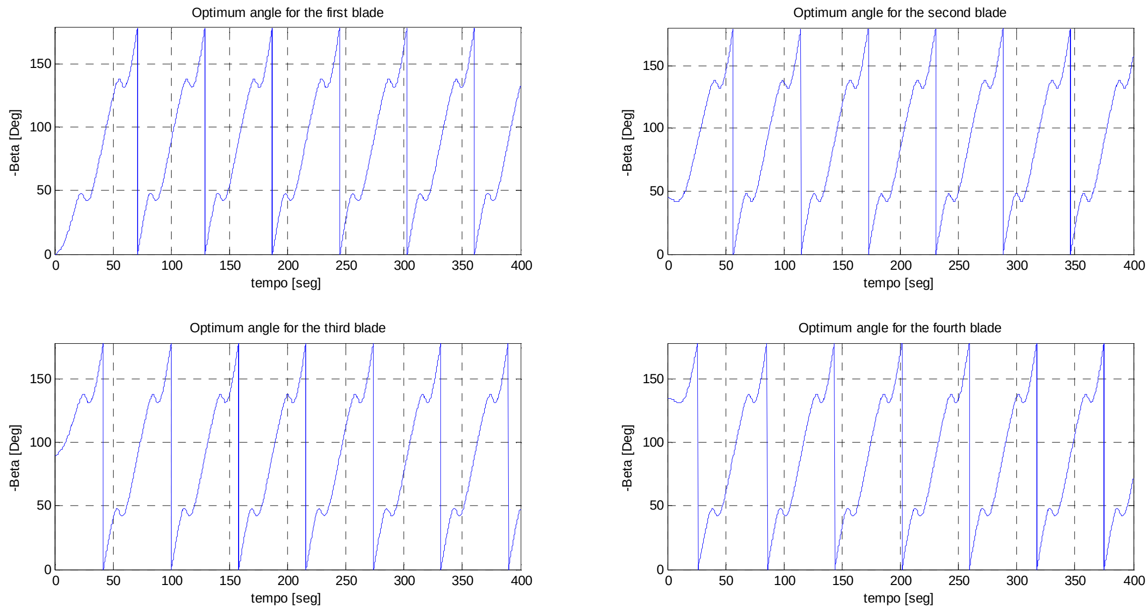

Figure 11. VAWT optimal angles with load

When considered the simulation with load, the turbine speed converges in a lower velocity than wind source velocity, as shown in Fig. 12. It is because when the turbine velocity increases, the torque generated decreases, (Fig. 9). And due to keeping the load torque, velocities will decrease substantially, to compensate the opposite charge (In this case, the constant load).

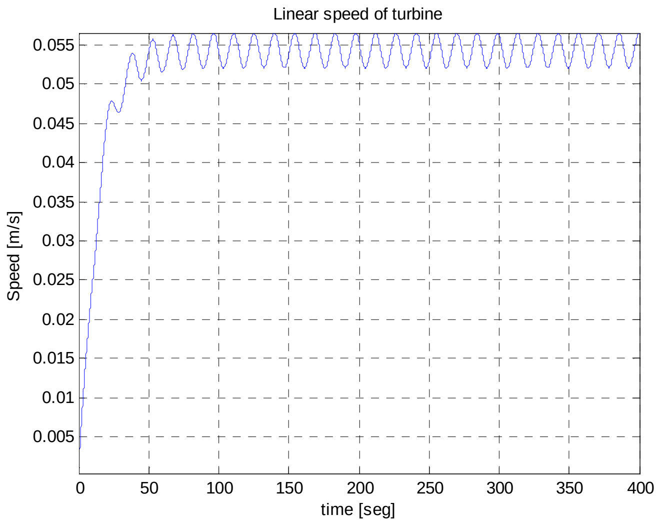

Figure 12. VAWT linear speed with load

Fig. 13 shows the torques in the simulated turbine with constant opposite load as function of time. It can see that the total turbine torque converges to constant opposite load. Thus, turbine adapts its blades to keep over the torque of the load value, and each blade has a periodical behavior.

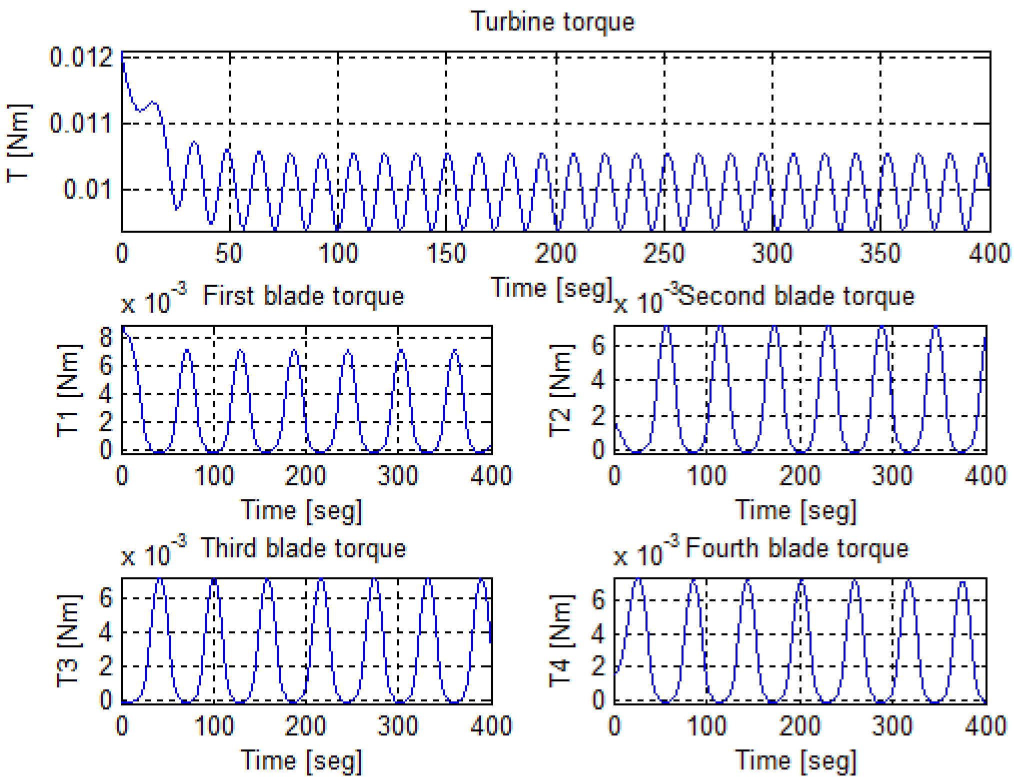

Figure 13. VAWT torques with constant load

3. CONCLUSIONS

This study was performed on a vertical axis wind turbine with symmetrical blades, in order to reduce the complexity of the calculations in the coefficients of drag and lift, and know that some blades of this type are easier to manufacture and therefore cheaper.

Most coefficients for lift and drag forces, were taken from previous work and properly referenced here. In the future it will be made more experiments to comment on the validity of the coefficients used for the simulations.

It is hoped that in future this type of turbines are economically viable and competitive opposite to other types of energy transformation, because of its easy maintenance and installation.

Because the vertical axis turbine simulated cannot exceed the wind speed, and besides that its advantage is that normally installed near the ground, where the average wind speed is relatively low, the direct application of such turbines is to generate relatively high torques, but not to work at high tip speed ratios.

4. REFERENCES

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