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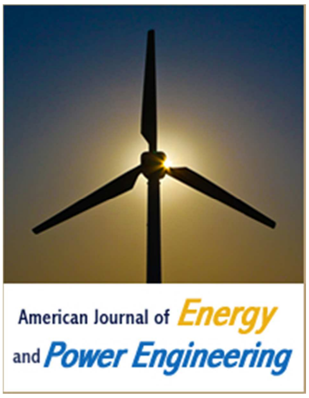

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VAWT Blade Aerodynamic Torque Analysis with the Help of Matlab Tools

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Abstract
In the course of this research the vertical axis wind turbine simulation model has been designed and verified using the MATLAB SIMULINK tool for blade aerodynamic force simulation. The research was based on the study of the real vertical axis wind turbine, which provided the basis for building the mathematical model. The mathematical model is used for simulation of the mechanical model of a one blade force and torque of the wind turbine. The main goal of the research was achieved and the designed model was successfully verified by the published data. The results showed that the simulation system is using correct calculations and the system can be used in future for further system development, for example, for developing the pitch system control strategy. The calculations can be used in simulation of the transient process for a real turbine with many blades over one rotor.

1. Introduction

Use of the renewable power resources has been the subject of active discussions and research for many years already. Exorbitant amounts have been invested to research this area, aiming to find the possibility to gain the high quality power from renewable energy resources (biomass, sun, wind) with the high degree of efficiency. Optimization of the performance factor in generation and use of energy remains a compelling and as yet unresolved issue in modern power production systems, the same being true for the renewable power industry [1].

A very important renewable system object of today is the vertical axes wind turbine with the power range 20 – 100kW. The reason why those wind turbine type is pushed in the market is that for the given power range the system is cheaper compared to the horizontal axes wind turbine, however the final solution has not been developed as yet for the VAWT system to achieve the best power performance and to ensure the cheapest production prices [2]. In general, VAWT is less productive compared to the HAWT system, yet there is just one final solution how to improve VAWT performance. This solution is the pitch control system for the wind turbine that would control the angle of attack of the blades. [3]

VAWT system is less complex, however, for future development of the pitch control system the proper analysis of the angle of attack should be performed [4]. For analysis of the pitch system it is very important to perform very accurate wind turbine rotor torque calculations real time simulation. This will allow the system to be used in real time simulations and will help to find the best solution in developing the pitch system control strategy [5].

The aim of the paper is to perform the real time simulation in MATLAB SIMULINK for VAWT blade force calculations with a set of all geometric data points taken from a real turbine.

2. Materials and Methods

In March 2015, in Jelgava the experimental research of Darrieus type vertical axis wind turbine was performed. According to the specification, the turbine capacity range is 0-50kW. The turbine dimensions are: width 10m and diameter 10m. The turbine consists of 3 blades with symmetrical assemblymen with 120 deg between each blade. VAWT blade type is NACA 0018 with no pitch control system (Fig.1.) [6].

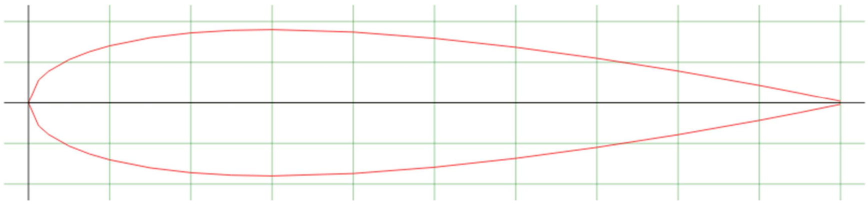

Fig. 1. *NACA0018 profile design*

No actual measurements were performed in the course of the research and the research results will be compared to other published data. During the period of mathematical modeling of the turbine process, information available from other researchers will be used to analyze the results of mathematical model before performing the actual pitch system tests [7].

The wind turbine shaft rotational torque T_{wind} depends on the four major parameters. It is directly proportional to the wind velocity V cube multiplied by the turbine efficiency η and the turbine rotor radius (R·L), and inversely proportional to the angular speed ω. The speed of wind is the most important parameter. The wind turbine shaft rotation torque can be calculated with the help of the following expression:[8]

$$T_{wind} = \frac{\rho \cdot 2 \cdot R \cdot L \cdot \eta \cdot V^3}{2 \cdot \omega}, \tag{1}$$

where T_{wind} – wind turbine torque, Nm;

- V – wind speed, $m \cdot s^{-1}$;
- L = 10 – length of the blades, m;
- R = 5 m – wind turbine rotor radius;
- ρ = 1.225 $kg \cdot m^{-3}$– air density;
- η = 0.275 – wind turbine efficiency.

Aerodynamic efficiency of the wind turbine is dependent upon the relation between the tangential speed of the tip of a blade and the actual speed of the wind expressed as the tip speed ratio - λ. For an experimental wind turbine the value of λ=3. Any deviation from the most efficient speed relation results in decrease of the efficiency ratio.[9]

$$\lambda = \frac{\omega \cdot R}{V}, \tag{2}$$

where ω – wind turbine angular speed, $rad \cdot s^{-1}$;

The aerodynamic process is described by many factors but one of the primary data is the wind turbine solidity and wind quality. This information is described by the Reynolds Number, R_e. Reynolds Number is calculated as follows [10]:

$$\mathrm{Re} = \frac{InertialForces}{ViscouseForces} = \frac{\rho \cdot V \cdot l}{\mu} = \frac{V \cdot l}{\upsilon}, \tag{3}$$

where l – wind turbine blade chord length, m;
υ – kinematic viscosity of the air, m2·s-1 (Table.1);
μ – dynamic viscosity of the air, kg·s·m-2;

Table 1. *Kinetic viscosity correlation to air temperature*

Temperature -*t* (°C)	**Density -ρ (kg·m^{-3})**	**Kinematic Viscosity - *υ* x 10^{-6} (m^2·s^{-1})**
-50	1.534	9.55
0	1.293	13.30
20	1.205	15.11
40	1.127	16.97

The Reynolds number is a dimensionless value that measures the ratio of inertial forces to viscous forces and describes the degree of laminar or turbulent flow. Systems that operate with the same Reynolds number will have the same flow characteristics even if the fluid, speed and characteristic lengths vary [11].

Solidity provides us direct information of how much of the area that turbine blades sweep through (swept area), is occupied by the turbine blades. Solidity of the wind turbine is calculated as follows:

$$\sigma = \frac{n \cdot l}{2 \cdot R}, \tag{4}$$

where n – wind turbine blade count;
l – wind turbine blade length, m;

The next focus is on the forces calculated in the wind turbine blades. As mentioned before, the main target is not to focus on some unknown efficiencies of the turbine but to operate directly with the forces in the blades. When the wind acts upon the wind turbine blade, the kinetic energy from the air is transferred onto the blade with the help of the blade swept area [12].

If the turbine operates with no pitch control, then the calculation of the angle of attack, α is calculated from the angle of azimuth position of the rotor. The angle α is calculated as follows:

$$\alpha = \tan^{-1}[\frac{\sin\theta}{\lambda + \cos\theta}], \quad (5)$$

where θ – azimuth position of wind turbine rotor, deg;

Wind turbine analysis based on the forces in the wind turbine blades is a very important method since the actual turbine efficiency is unknown and it is impossible to apply calculations found in the classic methods referred to in many other papers. Aerodynamic blade shape parameters is the only available information on the possible efficiency of the blade but not of the whole turbine not to mentioned the whole of the vertical axes wind station [13] (Fig.2.).

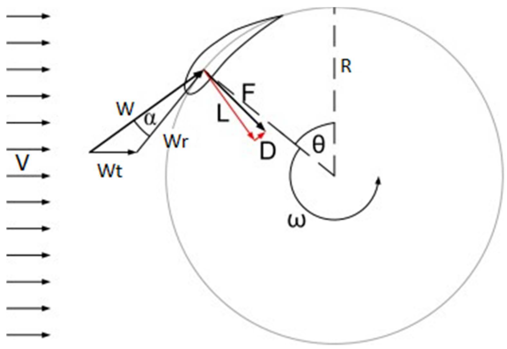

Fig. 2. *Blade forces and vector diagram*

When the wind energy goes into the wind turbine blade the force is calculated in accordance with the angle of the azimuth and the turbine rotation speed and wind speed (Fig.2.).

$$W_\tau = \cos\theta + \omega \cdot R$$
$$W_R = \sin\theta \cdot V \quad , \quad (6)$$
$$W^2 = W_R^2 + W_\tau^2$$

The second option how to calculate the angle of attack is the calculation from the wind vectors, which eventually will bring us to the same equation that is calculated based on the azimuth position of the rotor.

$$\alpha = \arctan[\frac{W_R}{W_\tau}], \quad (7)$$

The blade lift force is the potentially positive force, which sets the turbine into rotation. For calculation of the lift force projection on the speed vector the following expression is used:

$$L = \sin\alpha \cdot CL \cdot W^2 \cdot \frac{c \cdot l \cdot \rho}{2}, \quad (8)$$

where c – wind turbine blade chord length, m;
CL – lift force coefficient for NACA0018;

In the following situation the CL and CD coefficients are reliable data from the global information Site because the blade profiles have been tested in the laboratories for many years and thanks to the global web search engines the data is freely accessible for personal use. This is basically the reason why the NACA0018 was chosen for tests - all information regarding the profile aerodynamic is easily accessible (Fig.3.). The CL and CD coefficients are shown in the angle of attack in the position from -20°<α >20°.

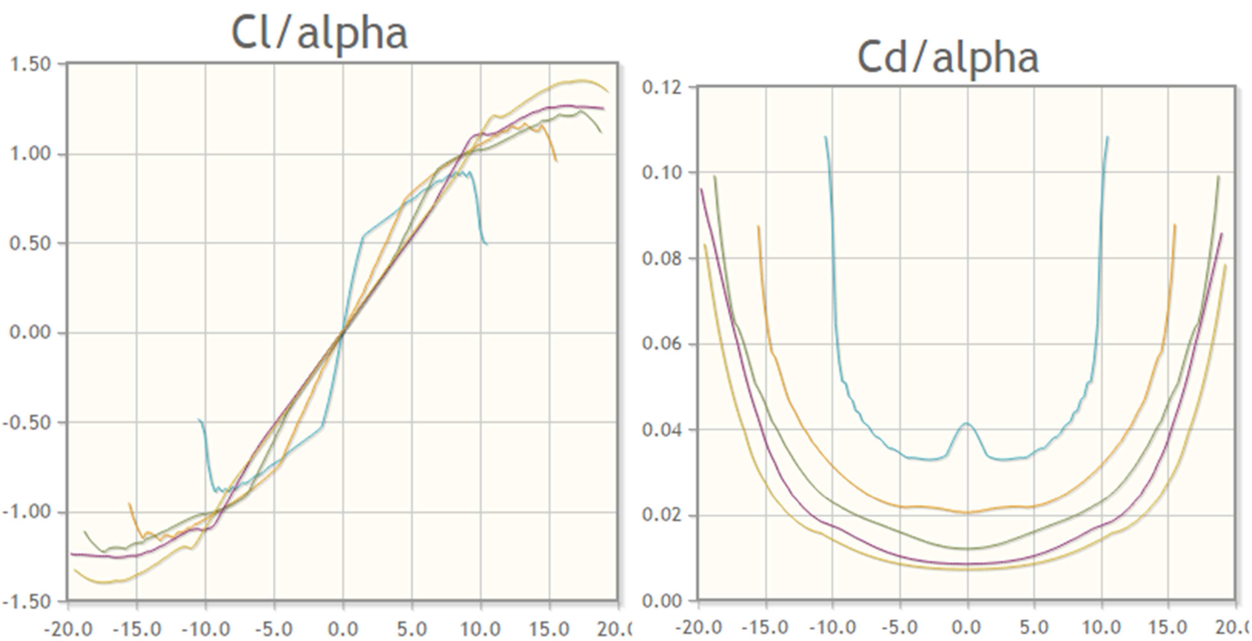

Fig. 3. *NACA0018 CL and CD as the function of azimuth angle*

Unused force of the wind turbine is the drag force in terms of energy production, its projection on the speed vector is calculated as follows:

$$D = \sin\alpha \cdot CD \cdot W^2 \cdot \frac{c \cdot l \cdot \rho}{2}, \tag{9}$$

where CD – drag force coefficient for NACA0018;

The total force F that acts upon the blade in the positive direction to push the turbine forward is calculated as follows:

$$\begin{aligned} F &= L - D \\ T &= R \cdot F \end{aligned}, \tag{10}$$

The turbine total torque T from the force produced by the wind energy is calculated on the basis of the wind force at the radius length. The final torque shows the actual working torque of the turbine, which can be reduced to the electrical generator and transformed into the electrical energy.

The system should be simulated and checked in the Matlab Simulink system for curve analyze.

3. Results and Discussions

The simulation model was divided into 2 separate systems. Math calculations referred to the turbine blades were done in Matlab Simulink for future use in the VAWT model simulation in Simulink, while the data plot and analysis were done it the Matlab editor (Fig.4.).

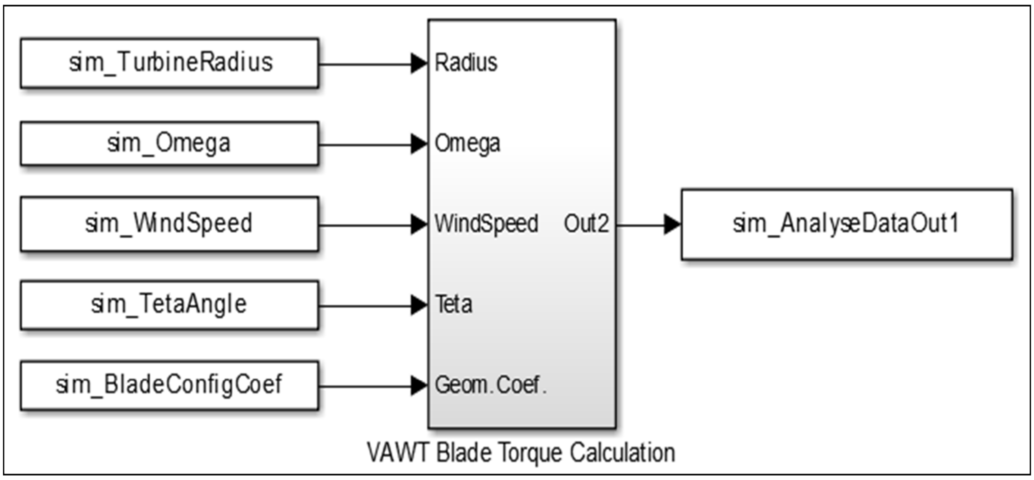

Fig. 4. *SIMULINK simulation system for the VAWT blade torque calculation*

VAWT blade torque simulation subsystem receives all the inputs from the set point written by the Matlab function running in Matlab Editor. The system calculated the data in accordance with the previously described equations (Fig.5.).

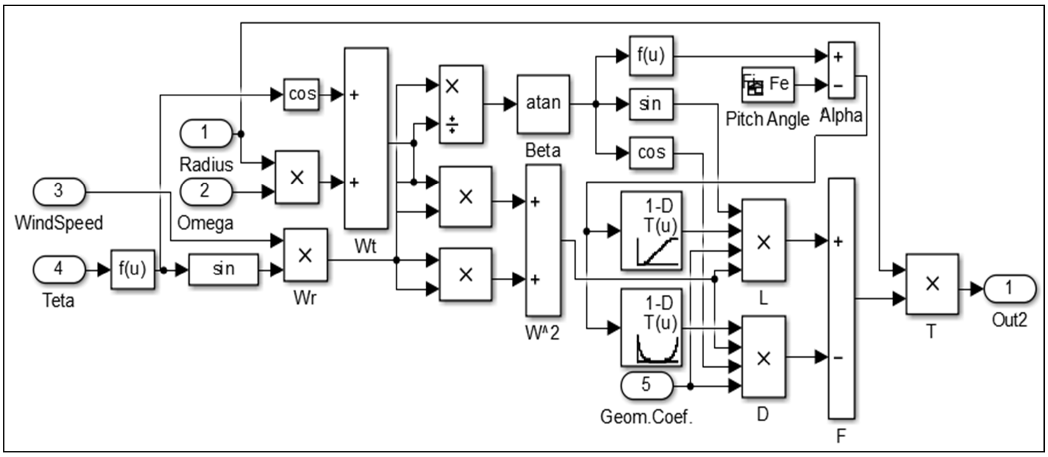

Fig. 5. *Internal Structure of 'VAWT Blade Torque Calculation' subsystem*

The simulation process is done in 3 main loops. The First loop is the part, where different TSR are used. The second loop is on each TSR simulating a lot of wind speed data. The Final loop is the internal turbine rotation across azimuth angle θ. During rotating around 360 deg the new simulation parameters are set and the simulation is run again. The simulation flow chart explains the system simulation program structure (Fig.6.).

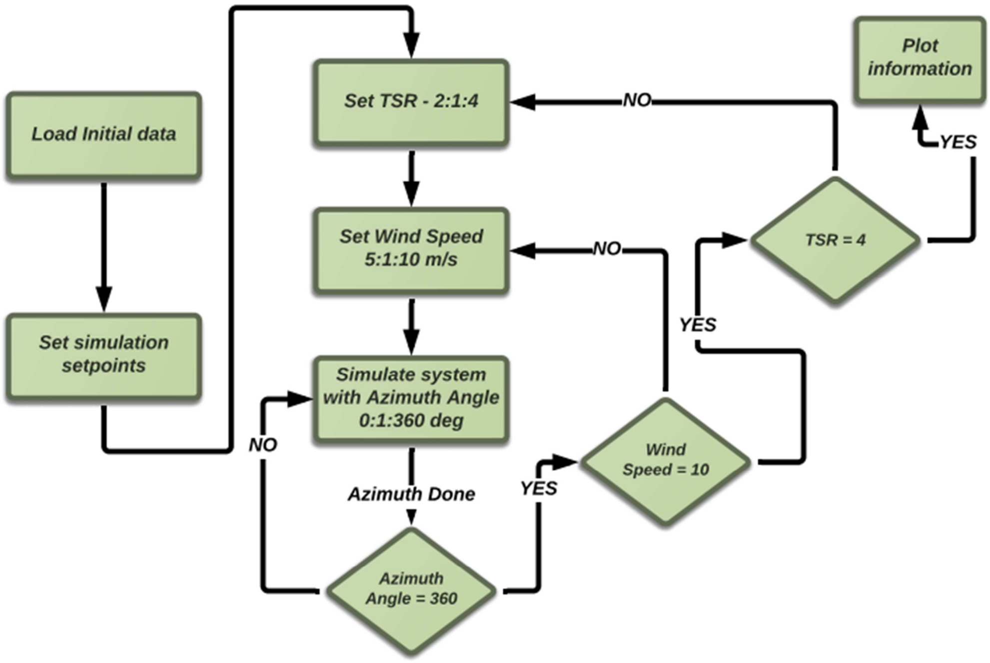

Fig. 6. *Matlab Editor and SIMULINK simulation system flow chart*

In the process of simulation 2 major information fields are analysed. The first field to compare the simulation code to the other methods is the angle of attack α simulation. The second important information is the wind turbine rotor torque produced by one blade on the rotor with no pitch control and with the stall angle of attack α (Fig.7.).

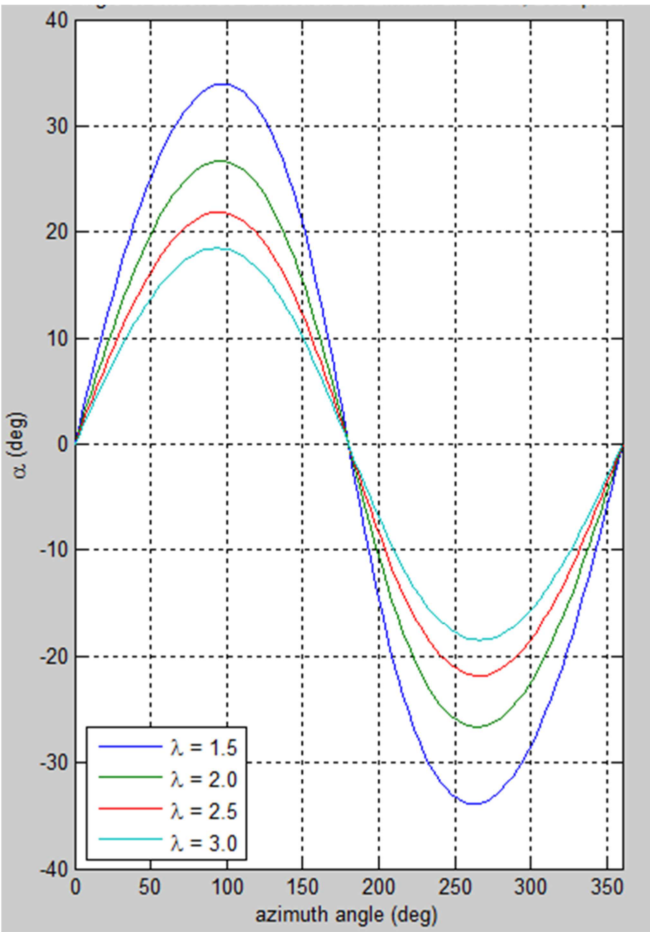

Fig. 7. *Angle of attack α as the function of azimuth angle θ*

The angle of attack in the period of rotation from 0° – 180° is symmetrical to the curve in period 181°-360°, which shows that the calculations are right. In the period 0°-180° the first half of the trend is symmetrical at the angle 90°, which shows that the system mathematical calculations is correct.

The blade toque shape depends on the type of the VAWT blade profile. At present, the testing is done using NACA0018 blade profile, but by changing the profile data for the CL and CD coefficients the simulation system will produce the data for another blade type (Fig.8.).

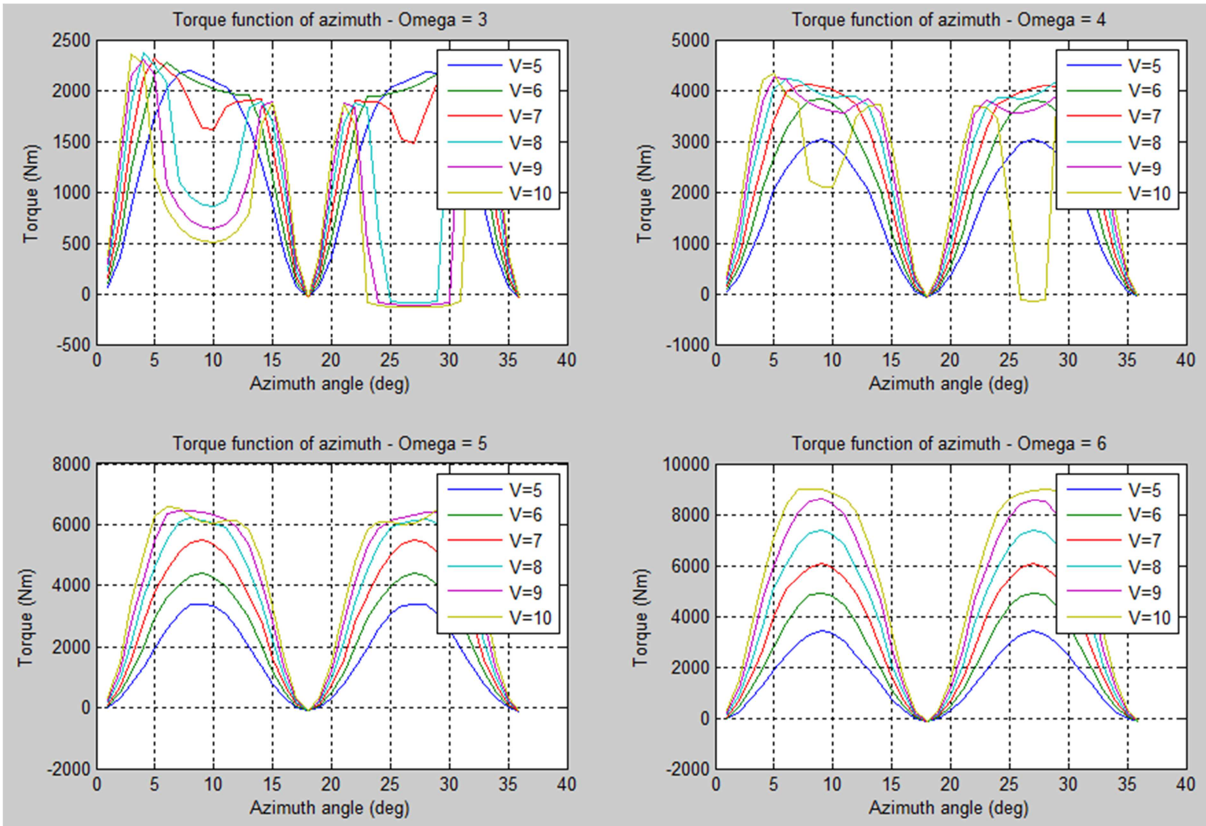

Fig. 8. *Blade produced torque as the function of azimuth angle α at the different rotor angular speed ω.*

4. Conclusions

1. For simplicity of use the aerodynamic torque calculations can be implemented in other simulation systems, where the main goal is vector calculations by using the necessary VAWT parameters.
2. Matlab Editor and Simulink analysis code can be used for future simulation of the pitch control or turbine control.
3. The simulation system is easily adjustable for other VAWT dimensions and configurations, since all calculation implementation is done with the help of simple math equations found in classical aerodynamics.

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