Modelling and Control of a Wind Turbine

J. Genov, G. Venkov, B. Gilev

Key Words: *Wind turbine model; control system*

Abstract. *A mathematical model of the system consisting of wind turbine, gear box and asynchronous generator is presented. The oscillation of tower tip is modeling. The behavior of the system for two different wind speeds was studied. One controller, which provides a mode of frequency stabilization in over-nominal wind speed, is developed. Then other controller, which provides a mode of maximum power generation in under-nominal wind speed, is developed. Provided is switching between two controllers without adverse transients responds.*

1. Introduction

The cost of electricity from wind turbines (WT) depends essentially on the initial investment and very expensive maintenance. Therefore keeping the operating mode and reducing dynamic loads leading to accidents is essential to reduce the price of produced electricity.

Wind turbines control is accomplished through changing the electrical characteristics of the generator and changing the pitch angle. Also wind turbines are equipped with systems for regulating the orientation angles of the axis of the turbine against the wind and against the skyline.

Control systems based on the PID controllers are applied for power control to several large WT [12].

LQR controllers and a state space observer to control wind turbine power are used, by changing the angle of attack of blades [7,13].

The dynamic model of the WT has significant nonlinear characteristics, usually associated with aerodynamic interactions. Thus a controller designed for one operating point of the turbine may be ineffective and may even have worse performance in other ones. The design of multiple controllers for different working points is a possible solution [4] when controllers are switched with the change of the respective conditions. This is associated with undesirable transient response and therefore is used an approach for a smooth transition [2].

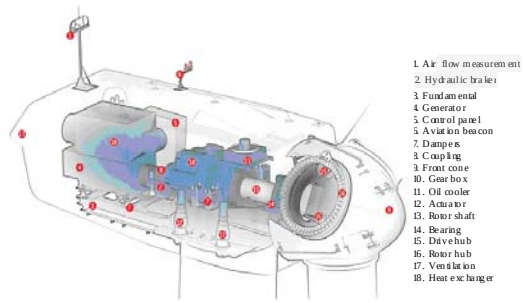

Figure 1. Structure of wind turbine

There are also used adaptive controllers [6], predictive controllers [5] and those based on the use of neural networks, fuzzy logic and genetic algorithms [2.11].

2. Dynamic Model of Wind Generator

Scheme of the constituting the generator is shown in *figure 1*.

2.1. Model of Interaction between the Wind and Wind Turbine

• Modelling the wind speed

The wind speed is modelled as the sum of the following components:

(1) $V_\infty(t) = v_a + v_r(t) + v_g(t) + v_{taw}(t) + v_t(t)$,

where

v_a – the average initial speed of the wind;

$v_r(t)$ – the component of linear increase in amplitude A_r;

$v_g(t)$ – the component of the wind gust speed, (under extreme conditions it is modelled as a stochastic component, depending on regional weather);

$v_{taw}(t)$ – the component takes into account the aerodynamic "shadow" of a tower. It causes harmonic components of the wind speed with frequencies multiple of the number of blades. In a 3-blade turbine the component with frequency three times greater of the turbine speed is essential;

$v_t(t)$ – the turbulent component due to roughness of the blades and wrapping processes. It is seen as a random process with spectral density which is determined by several methods:

Relation (1) is approximated as a normally distributed

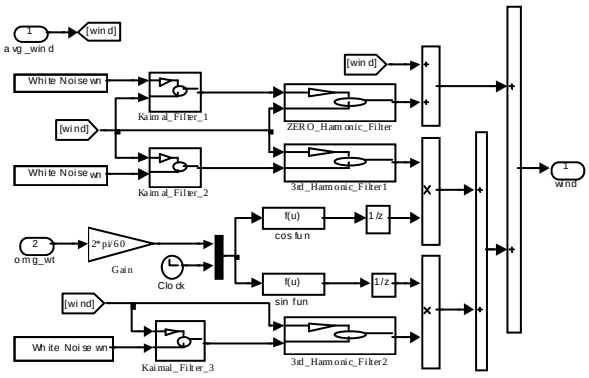

Figure 2. Program module in MATLAB-Simulink to generate the wind speed through the Kaimal filter [10]

random signal (white noise) which is passed through a Kaimal filter [10]. After this filter harmonic filters of second order are included , which increase the influence of harmonic components multiple to 3 (for 3-blade generators).

A structural diagram that realizes the wind speed according to (1) is shown in *figure 2*.

• Model of the aerodynamic interaction between wind and the blades

Figure 3 shows the basic aerodynamic characteristics of the wrapping.

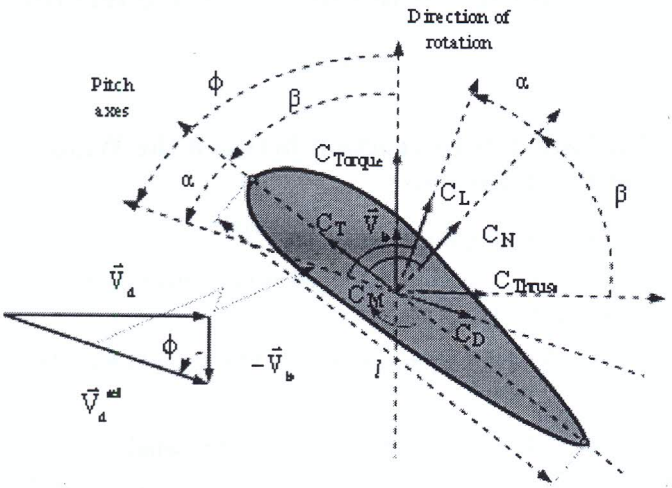

Figure 3. Aerodynamic wrapping

Designated parameters are the following:

V_d – the wind speed in the turbine disc;

V_b – thespeed in the corresponding section of the blade;

β – the pitch angle (angle of attack of the blades);

α – the slope angle of the blades;

ϕ – the angle of the flow;

C_N – the coefficient of the normal force;

C_T – the coefficient of the tangential force;

C_L – the lift force coefficient;

C_D – the coefficient of the moving pressure force;

C_{Torque} – the coefficient of the rotating force;

C_{Thrust} – the coefficient of the axial force;

C_M – the torque coefficient;

l – the cross section length.

For control of the generator is used a servo mechanism that rotates the blades is used. This mechanism changes the angle β, respectively the angle of the attack α. This control is known as Pitch control.

Figure 4 shows the wrapping for two values of the angle β – 5^0 and 10^0. It is seen that at an angle greater than a specific value, the flow is moving away from the end of the blade. The difference in pressure is diminishing and thus the torque and speed are reduced respectively.

In *figure 5* is shown the change in wrapping airflow.

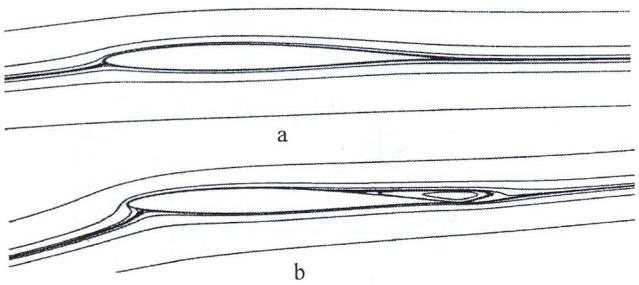

Figure 4. Traffic flow at the different blade angles: a) 5^0 and b) 10^0

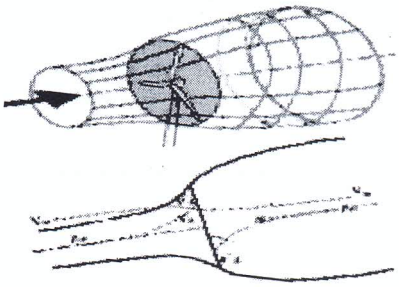

Figure 5. Wrapping airflow

There are considered three major sections:

– by wrapping with characteristics: the speed V_∞ and the pressure p_∞;

– in the turbine disk: the speed V_d and the pressure p^+_d before the disc and the pressure p^-_d after the disc;

– in the airflow trace after the turbine- the speed V_W.

Changing the speed of the turbine disk can be described by the relationship

(2) $V_\infty - V_d = aV_\infty$, where $a = (V_\infty - V_d)/V_\infty$ is a coefficient of reduction.

Using the Bernoulli's equation and the theorems of changes in momentum and kinetic energy the following relations obtained:

– the relationships for speeds:

$$(3)\quad \left| \begin{array}{l} V_d = \dfrac{V_\infty + V_w}{2} = (1-a)V_\infty,\ V_w = (1-2a)V_\infty, \\ V_\infty - V_w = 2aV_\infty,\ V_\infty + V_w = 2(1-a)V_\infty \end{array} \right. ;$$

– for the power of the wind turbine

(4) $P_{wtr} = 0,5\rho AV_d\left(V_\infty^2 - V_w^2\right) = 2a(1-a)^2\rho AV_\infty^3$,

where: ρ is the air density;

$A = \pi R^2$ is the area of the turbine disk;

R is the radius of the turbine.

– for the axial force

(5) $F_{Thrust} = C_{Thrust}\,0,5\rho AV_\infty^2$, where $C_{Thrust} = 4a(1-a)$.

The ideal power of the turbine is achieved in $V_d = V_\infty$ and $V_w = 0$ it is

(6) $P_{wtr}^{\ i} = 0,5\rho AV_\infty^3$.

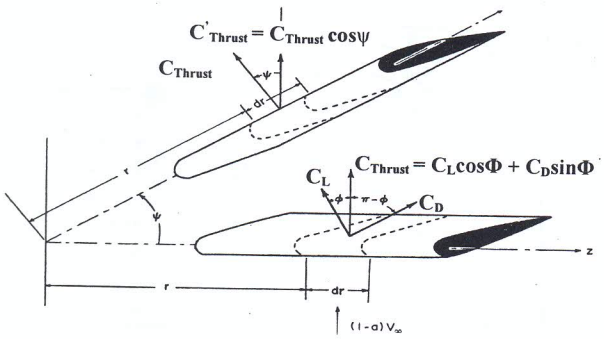

Figure 6. Change of the wrapping angle along the blade

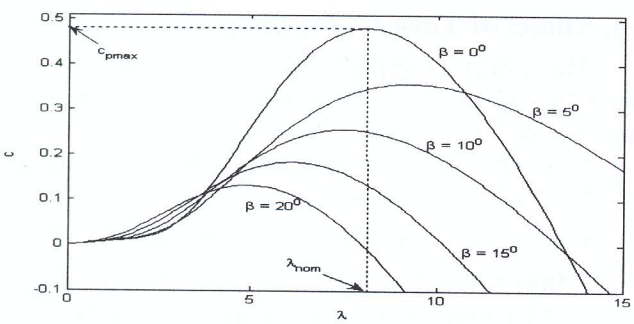

Figure 7. The characteristic $C_p(\lambda)$ of the turbine

The ratio of actual to ideal power is given by the power coefficient

(7) $C_p = P_{wtr} / P_{wtr}^{i} = 4a(1-a)^2$.

Another effect is the energy transformation into a rotational movement of the flow. This is appearing into the disk area and the turbine trace.

From the theorems of the amount of movement, the kinetic moment of the axial force, the torque and the mechanical power it is obtainled:

(8) $F_{Thrust} = C_{Trust} 0{,}5\rho A V_{\infty}^{2}$,

where: $C_{Trust} = 8\cos^2(\psi(R))\lambda^{-2}\int_0^{\lambda}(1-a)a\lambda_L d\lambda_L$;

$\psi(r)$ the angle of twist of the blade around the longitudinal axis – *figure 6*;

r – the radius of the current section;

$\lambda = R\,\Omega_{wtr}\cos(\psi(R))/V_{\infty}$, $\lambda_L = r_L\,\Omega_{wtr}/V_{\infty}$,

$r_L = r\cos(\psi(r))$;

Ω_{wtr} – the angular velocity of the turbine;

(9) $T_{wtr} = C_p P_{wtr}/\Omega_{wtr}$

where: $C_p = 8\cos^2(\psi(R))\lambda^{-2}\int_0^{\lambda}(1-a)a'\lambda_L^{3}d\lambda_L$;

$a' = 0{,}5\Omega_d/\Omega_{wtr}$;

Ω_d – the angular velocity of the disc flow;

(10) $P_{wtr} = C_p P^{i}_{wt}$.

For C_p it can be used the approximation [10]:

(11) $C_p(\lambda,\beta) = c_1(c_2/\lambda_1 - c_3\beta - c_4)e^{-c_5/\lambda_1} + c_6\lambda$,

where: $\lambda_1^{-1} = (\lambda + c_7\beta)^{-1} - c_8(\beta^3+1)^{-1}$;

$c_1 \div c_8$ experimentally determined coefficients, for the respective constructive solution.

The Characteristic $C_p(\lambda)$ of the specific turbine [9] is shown in *figure 7*.

2.2. Model of Mechanical Part of the Generator and Gearbox

A diagram of the gearbox and the mechanical part of generator is shown in *figure 8*. It is presented as a dual-mass dynamic model with reducing the corresponding masses to the turbine and generator.

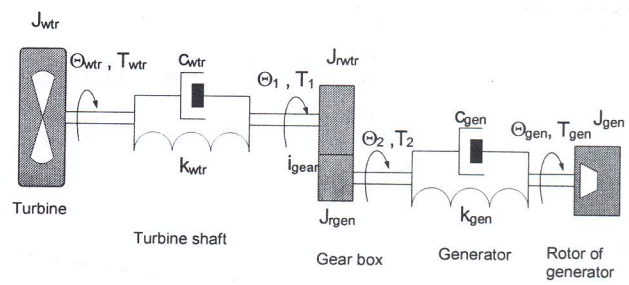

Figure 8. Mechanical model

The Differential equations describing the model are:

$$
(12)\quad \left|\begin{array}{l}
J_{wtr}\ddot{\theta}_{wtr} + c_{wtr}(\dot{\theta}_{wtr} - \dot{\theta}_1) + k_{wtr}(\theta_{wtr} - \theta_1) = T_{wtr}, \\
J_{rwtr}\ddot{\theta}_1 - c_{wtr}(\dot{\theta}_{wtr} - \dot{\theta}_1) - k_{wtr}(\theta_{wtr} - \theta_1) = -T_1, \\
J_{rgen}\ddot{\theta}_2 + c_{gen}(\dot{\theta}_2 - \dot{\theta}_{gen}) + k_{gen}(\theta_2 - \theta_{gen}) = T_2, \\
J_{gen}\ddot{\theta}_{gen} - c_{gen}(\dot{\theta}_2 - \dot{\theta}_{gen}) - k_{gen}(\theta_2 - \theta_{gen}) = -T_{gen},
\end{array}\right. ,
$$

where: $\dot{\theta}_{wtr} = \Omega_{wtr}$, $\dot{\theta}_1 = \Omega_1$, $\dot{\theta}_2 = \Omega_2$;

J_{wtr} – the mass moment of inertia of the turbine;

k_{wtr} – the torsion stiffness of the turbine shaft;

c_{wtr} – the torsion damping coefficient of the turbine shaft;

i_{gear} – the gear reduction ratio;

Ω_1 – the input angular speed of gearbox;

J_{rwtr} – the mass moment of inertia of the gearbox, reduced to the turbine shaft (coordinate θ_1);

$\Omega_2 = i_{gear}\,\Omega_1$ – the output angular speed of gearbox.

J_{rgen} – the mass moment of inertia of the gearbox, reduced to the generator shaft (coordinate θ_2);

T_1 – the input torque of the gearbox;

$T_2 = T_1/i_{gear}$ – the output torque of the gear;

k_{gen} – the torsion stiffness of the generator shaft;

c_{gen} – the torsion damping coefficient of the generator shaft;

Ω_{gen} – the angular velocity of the rotor of the generator;

θ_{gen} – the angular position of the rotor of the generator;

J_{gen} – the mass moment of inertia of the generator;

T_{gen} – the electromagnetic moment of the generator.

2.3. Model of Electrical Part of Generator

A model of asynchronous generator with wound rotor is examined, decomposition by d-q axes was applied, shown in *figure 9*. This model is described by a system of differential equations:

$$(13)\quad \left|\begin{array}{l} V_{qs} = R_s i_{qs} + \dot{\varphi}_{qs} + \omega_e \varphi_{ds} \\ V_{ds} = R_s i_{ds} + \dot{\varphi}_{ds} - \omega_e \varphi_{qs} \\ V'_{qr} = R'_r i'_{qr} + \dot{\varphi}'_{qr} + (\omega_e - \omega_r)\varphi'_{dr} \\ V'_{dr} = R'_r i'_{dr} + \dot{\varphi}'_{dr} - (\omega_e - \omega_r)\varphi'_{qr} \\ T_{gen} = 1,5p(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds}) \end{array}\right.$$

where:

$$\varphi_{qs} = L_s i_{qs} + L_m i'_{qr}, \varphi'_{qr} = L'_r i_{qr} + L_m i_{qs}$$

$$\varphi_{ds} = L_s i_{ds} + L_m i'_{dr}, \varphi'_{dr} = L'_r i_{dr} + L_m i_{ds}$$

$$L_s = L_{is} + L_m,\ L'_r = L'_{lr} + L_m$$

L_m – the magnetization inductance;

$\theta_r = p\theta_e$ – the electrical circuit position;

p – the number of pairs of poles;

ω_e – the electric frequency;

$\omega_r = \Omega_{gen}$ – the angular rotor frequency;

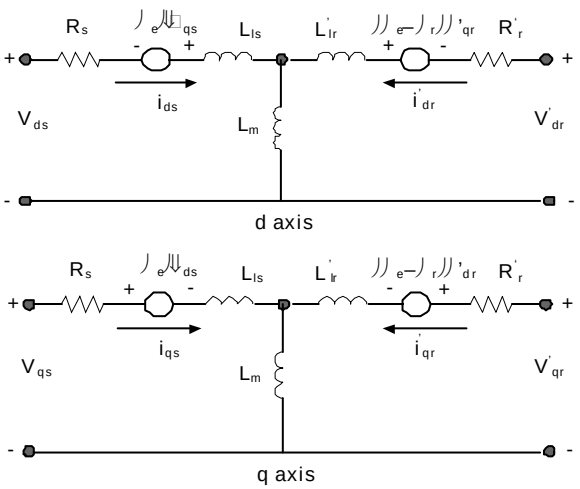

Figure 9. Model of asynchronous generator with wound rotor

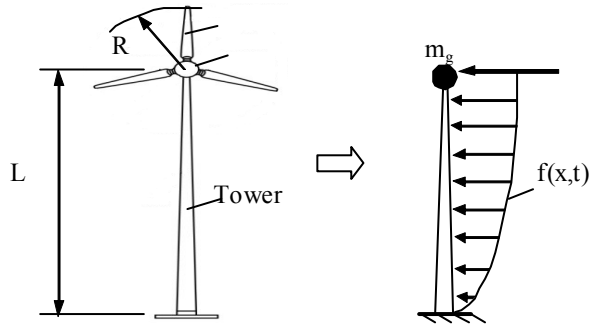

Figure 10. Model of a tower

the indices s, r and ' mean respectively stator and rotor and stator reduced variables.

2.4. Model of Tower Vibrations

The tower is represented as an elastic beam, *figure 10*. The cab is modeled through concentrated in the tip mass. We consider the axial force load on the turbine and the distributed load on the tower height f (x, t), determined by the relationship [3]

$$(14)\quad f(x,t) = C_D k_L 0,5\rho_a V^2(x,t) D(x),$$

where: D(x) is the current external diameter of the cross-section of the tower, k_L is the correction factor related to a cylinder with finite length, C_D is an experimentally determined coefficient of the tower drag, depending on the Reynolds number [15].

The Height change in the wind speed is set by the relationship [8]:

$$(15)\quad V(z) = V_{10}\left(z / z_0\right)^{\alpha},$$

where: V_{10} is the wind speed at a height of 10 m;

α the factor takes into account the type of place (of 0.16 for marine areas and plains to 0.4 for urban areas);

z_0 is the height above the ground to which it is assumed that the wind speed is zero (0,01 ч 0,2 m).

The Dynamic behaviour of the tower is described by the partial non-homogeneous differential equation of fourth order:

$$(16)\quad \frac{\partial^2}{\partial z^2}\left(EI(z)\frac{\partial^2 w(z,t)}{\partial z^2}\right) + 2n_b\rho A_t(z)\frac{\partial w(z,t)}{\partial t} + \rho A_t(z)\frac{\partial^2 w(z,t)}{\partial t^2} = f(z,t) + F_{thrust}(t)\delta(z-L)$$

where ρ, E and n_b are respectively the mass density of the material, the modulus of elasticity and the damping coefficient, $A_t(x)$ and I(x) are the area and the moment of inertia, L is the height of the tower, z is the current vertical coordinate, w is the transverse moving of the beam points, *ä* is the Dirac function, δ is the mass of the cab.

The boundary and initial conditions are:

$$(17)\quad \left|\begin{array}{ll} w(0,t)=0, & \frac{\partial w(0,t)}{\partial z}=0,\ \frac{\partial^2 w(L,t)}{\partial z^2}=0,\ \frac{\partial^2}{\partial z^2}\left(EI(L)\frac{\partial w(L,t)}{\partial z}\right) = -m_2\frac{\partial w^2(L,t)}{\partial t^2} \\ w(z,0)=0, & \dot{w}(z,0)=0 \end{array}\right. .$$

The solution of (16) is found by the finite element method. For this purpose the beam is divided into N in number finite elements of length *l*, with two degrees of

freedom at each node: the moving $w(z,t)$ and the rotation

$$\theta(z,t)=\frac{\partial w(z,t)}{\partial z}.$$

In a separate element geometry and mass characteristics are constant.

Then (16) is transformed into a system of 2N+2 numbers of ordinary differential equations of second order:

$$M\ddot{q}_t + C\dot{q}_t + Kq_t = F, \tag{18}$$

where: M, C, K are respectively the mass, elastic and dissipative matrices and their formation is under the approach described in [14]; q_t is the vector of generalized coordinates with dimension 2N (taking into account the boundary conditions for z=0).

Taking into account the boundary condition for z = L, for the matrices of mass and wind action it is obtained

$$M^* = \begin{bmatrix} m_{11} & \dots & m_{l(n-1)} & m_{1n} \\ \dots & \dots & \dots & \dots \\ m_{(n-1)l} & \dots & \boxed{m_{(n-1)(n-1)} + m_g} & m_{(n-1)n} \\ m_{n1} & \dots & m_{n(n-1)} & m_{nn} \end{bmatrix}, \quad F^* = \begin{bmatrix} l\left(f(z_1,t)+f(z_2,t)\right)/2 \\ l^2\left(f(z_1,t)-f(z_2,t)\right)/12 \\ l\left(f(z_2,t)+f(z_3,t)\right)/2 \\ l^2\left(f(z_2,t)-f(z_3,t)\right)/12 \\ \dots \\ \boxed{lf(L,t)/2+F_{Thrust}(t)} \\ l^2 f(L,t)/12 \end{bmatrix}. \tag{19}$$

The element stresses are determined by the relationship:

$$\sigma_x(z,t) = -E\frac{\partial^2 w(z,t)}{\partial z^2}\frac{D(z)}{2}, \tag{20}$$

where D(z) is the current diameter of the tower.

2.5. Full Model

In the Simulink-MATLAB environment models of wind speed, wind turbine, tower, generator and gear box are integrated. Adding the two PID controllers (from next point) the full model is obtained as shown in *figure 11*.

The Wind speed model from *figure 2* is placed in a block named "Wind Model ZA-2". The Input of this block is fed with an average wind speed and on the output we obtain a random realisation of that speed. The turbine's model is placed in the block "Wind Turbine". In the outputs of this block we obtain mechanical torque and force applied

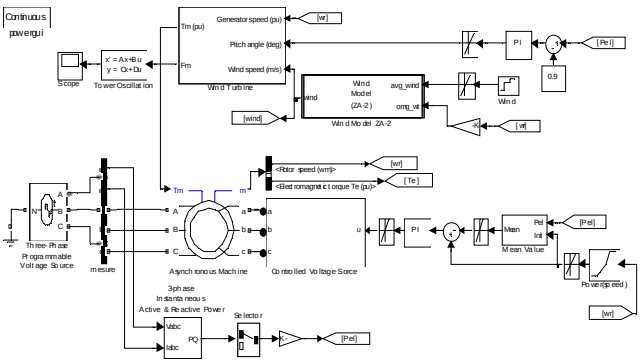

Figure 11. Full WT model in the Simulink-MATLAB

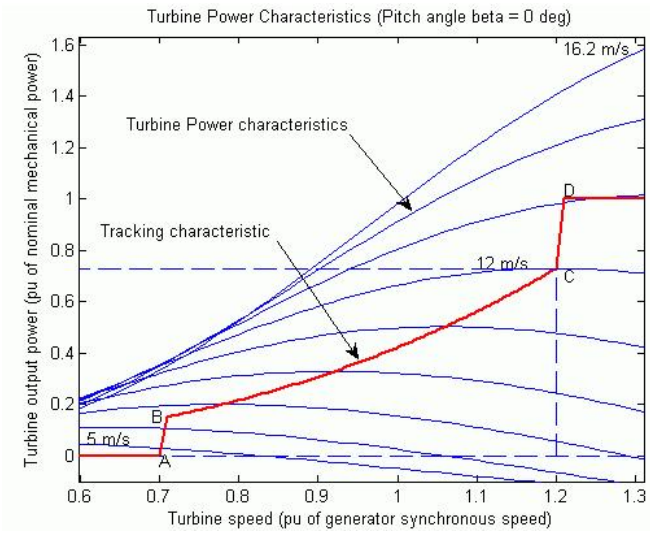

Figure 12. Tracking characteristic

at the tower's tip. The models of electrical and mechanical part of the generator are located into one block, named "Asynchronous Machine". After standard change of variables the system (18) is reduced to a system of first order ODE. The resulting system is placed in the block "Tower Oscillations". This block simulates the vibrations of tower tip. "Tracking Characteristic" of *figure 12* is placed in the block "Power (speed)". This block generates the reference power by under-nominal wind speed. Since the measured output power of the generator oscillates a placement of block "Mean value" is needed. This block averages the input signal for one period. One PID controller from *figure 11* works in under-nominal wind speed while the other works in over-nominal wind speed.

3. Control by Two PID Regulators

The main goals of control are the efficiency and high quality of produced electricity as well as maintaining the lowest possible dynamic loads in the elements of the system. These goals are usually conflicting, which requires searching for optimal compromissary strategies and solutions. Therefore, the best efficiency is achieved if we implement a balanced relationship between these goals.

In low wind speed, the generated power is lower than the nominal output power. So in this area the main task of the control system is to increase the output power of the wind turbine. It is known that for one specific wind speed maximum efficiency is achieved only for one specific generator speed. Changing the generator's speed leads to production of electric power with variable frequency. For stabilizing the frequency the wind turbine is connected to the network through AC-DC-AC converter. In these wind turbines the rotor speed can be varied by changing rotor's voltage.

In high wind speed the maximum possible output power is greater than the nominal power of the wind turbine. Thus the power must be reduced for providing operation without overloading. The effective method for reducing the gener-

ated energy is changing the pitch angle β.

The boundary between the two regions is the lowest wind speed V_{nom} at which the turbine reaches nominal power.

In the first region of control, the wind speed is $V_{min} < V_{\infty} < V_{nom}$. In this region the pitch angle is zero and the voltage of the rotor is changed. This is done with the PID controller which has the following control law

$$u_{rotor} = K_p^1 (P - P_{ref}) + K_i^1 \int_{t_0}^{t} (P - P_{ref})^2 dt ,$$

where K^1_p and K^1_i are the proportional and integral gain, and P_{ref} is the reference output power of the generator, which is function of wind speed. This power is determined by the Tracking Characteristic shown in *figure 12*.

In the second region of control, the wind speed is $V_{nom} < V_{\infty} < V_{max}$. In this region the wind speed is enough for the generator's work at nominal power. Hence the PID regulator controlling the electric part is inactive, while the PID regulator controlling pitch angle is operational. This PID regulator makes the following control law

$$\beta = K_p^2 (P - P_{nom}) + K_i^2 \int_{t_0}^{t} (P - P_{nom})^2 dt ,$$

where K^2_p and K^2_i are the proportional and integral gain, and P_{nom} is the nominal output power of the generator. The aim of that control is avoiding work with power greater than nominal.

For the wind speed which is outside the two controlled regions the generator is turned off.

The two PID controllers are tuned so that when one of them is operational, the other is off. This is because the settings are as follows: when one controller produces a positive control signal, the other produces negative. Besides, after these controllers the function which cut off the negative control signal is placed and in that case on their output we obtain zero.

4. Numerical Results

With the model from *figure 11* some results are simulated, shown in *figures 13-20b*.

The behaviour of the system for two different wind speeds under-nominal and over-nominal was studied – *figure 13*.

In accordance with the settings the pitch angle at low speed is zero and increases at high speed – *figure 14*. At low wind speed the output generator power slowly raises – *figure18*, due to the change of rotor voltage – *figure15*. At the same time by strong wind speeds generates less power than the maximum possible, which prevents system overloading.

The settling time of the first controller is about 15 s – *figure 13*. Commensurable to that time is the duration of the transient responses on the second controller – *figure14*.

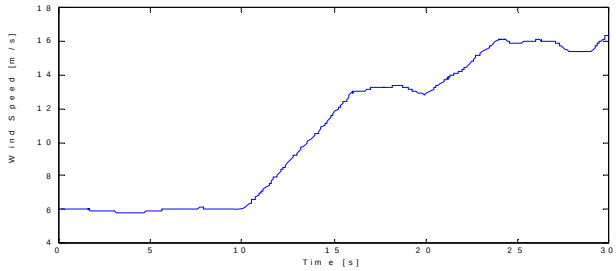

Figure 13. Wind speed

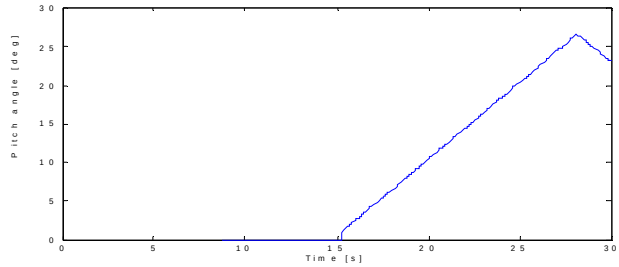

Figure 14. Pitch angle

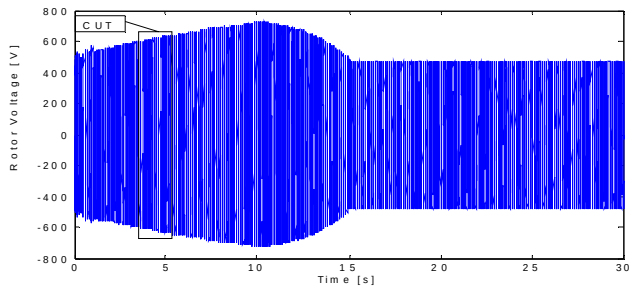

Figure 15a. Rotor control voltage

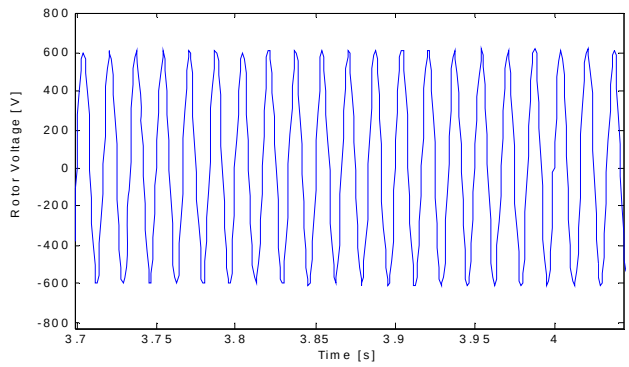

Figure 15b. Cut of rotor control voltage

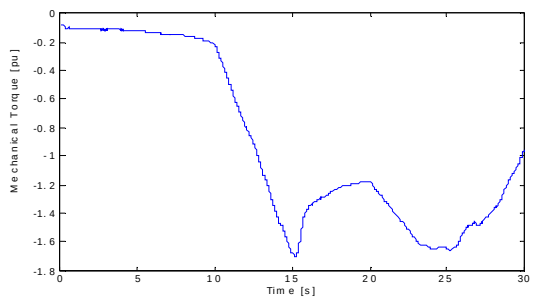

Figure 16a. Mechanical Torque by pitch angle and rotor voltage shown in figures 13 and 14

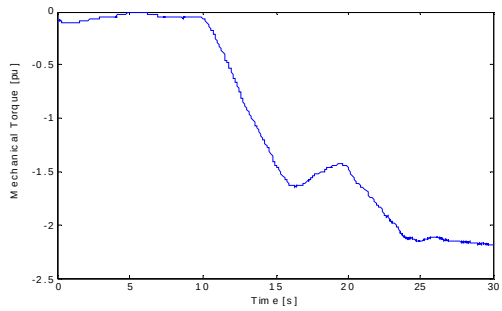

Figure 16b. Mechanical Torque by zero pitch angle and nominal rotor voltage

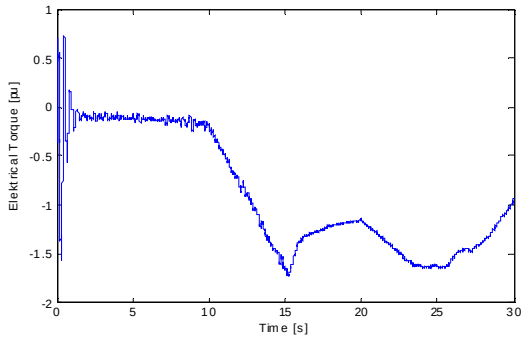

Figure 17a. Electrical Torque by pitch angle and rotor voltage shown in figures 13 and 14

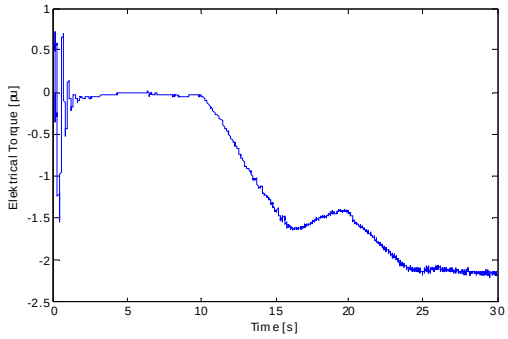

Figure 17b. Electrical Torque by zero pitch angle and nominal rotor voltage

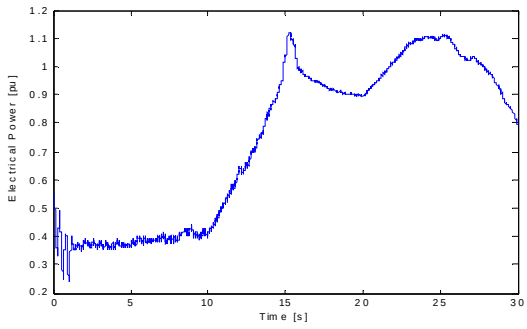

Figure 18a. Electric Power by pitch angle and rotor voltage shown in figures 13 and 14

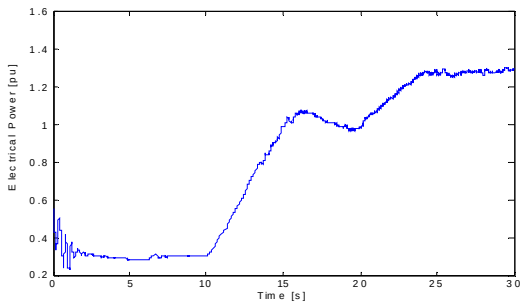

Figure 18b. Electric Power by zero pitch angle and nominal rotor voltage

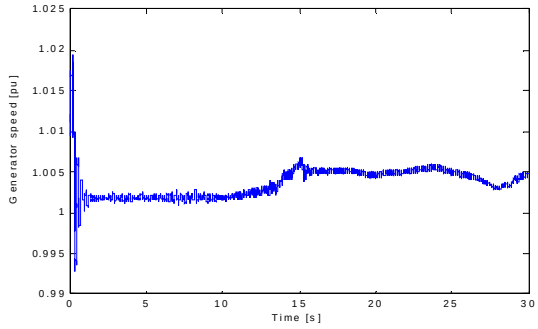

Figure 19a. Generator Speed by pitch angle and rotor voltage shown in figures 13 and 14

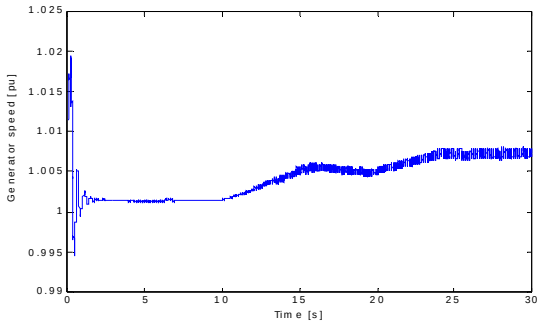

Figure 19b. Generator Speed by zero pitch angle and nominal rotor voltage

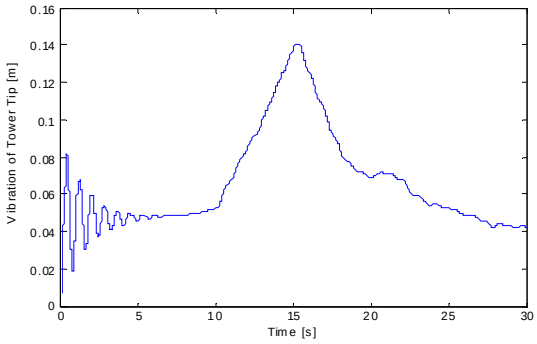

Figure 20a. Vibration of the tower tip by pitch angle and rotor voltage shown in figures 13 and 14

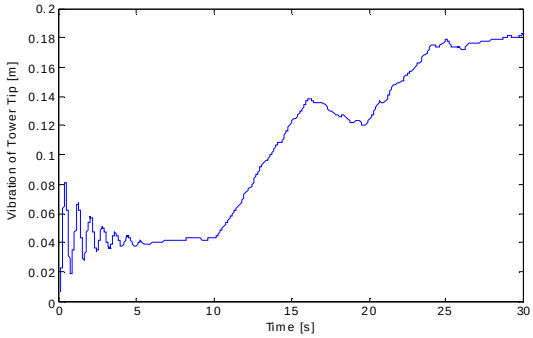

Figure 20b. Vibration of the tower tip by zero pitch angle and nominal rotor voltage

At low wind the torque slightly depends on the controllers – *figure 16* and *figure 17*.

The controllers have small impact of the speed of the rotor – *figure 19*.

Due to the control the maximum oscillation of the tip of the tower decreases by about 20% – *figure 20*.

Acknowledgment

This research was supported by the project "DO 02 – 348" sponsored by National Science Fund of Bulgarian Ministry of Education, Youth and Science.

Reference

1. Beljaars, A. Influence of Sampling and Filtering Measured Wing Gusts. – *Journal of Atmospheric and Oceanic Technology*, 4, 1987.

2. Bongers, P. Modelling and Identification of Flexible Wind Turbines and a Factorizational Approach to Robust Control. PhD Thesis, Department of Mechanical Engineering and Marine Technology, Delft University of Technology, 1994.

3. Tritton, D. Physical Fluid Dynamics, 2nd edition. Oxford University Press, New York, 1988.2.

4. Bottasso, C. L., and A. Croce. Scientific Report DIA-SR 09-01. Dipartimento di Ingegneria Aerospaziale, Politecnico di Milano, Milano, Italy, January 2009.

5. Findeisen, F., L. Imland, F. Allgoewer, and B. Foss. State and Output Feedback Nonlinear Model Predictive Control: An Overview. – *European Journal of Control*, 9, 2003,190-206.

6. Freeman, J. B., and M. J. Balas. An Investigation of Variable-Speed Horizontal-Axis Wind Turbines Using Direct Model-Reference Adaptive Control. Proc.of the 37th AIAA Aerospace Sciences Meeting and Exhibit, Reno,Nevada, 1999, 66-76.

7. Genov J., B. Gilev, Y. Slavchev, G. Venkov**.** Modelling and Control of Wind Turbine Tower Vibrations. American Institute of Physics, Conference Proceedings, 1293**,** 2010, 30-38.

8. Hansen, M. Aerodynamics of Wind Turbines, 2nd Ed., Earthscan, London, UK, 2008, 190.

9. Heier, S. Grid Integration of Wind Energy Conversion Systems. John Wiley & Sons, New York, 2005.

10. Iov, F., A. Hansen, P. Sorensen. Wind Turbine Blockset in Matlab/Simulink. Frede Blaabjerg, Aalborg University, 2004.

11. Karimi-Davijani, H. and All. Fuzzy Logic Control of Doubly Fed Induction Generator Wind Turbine. – *World Applied Sciences Journal*, 6 (4),2009, 499-508.

12. Kos, J. On Line Control of a Large Horizontal Axis Energy Conversion System and its Performance in a Turbulent Wind Environment. Proc. of the 13th Intersociety Energy Conversion Engineering Conference, U.S.A., 1978, 2064-2073.

13. Mattson, S. Modelling and Control of Large Horizontal Axis Wind Power Plants. PhD Thesis, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden, 1984.

14. Pasheva, V., G. Venkov, E. Chankov. A Finite Element Model of a Wind Turbine Tower, American Institute of Physics, Conference Proceedings, 1293**,** 2010, 79-80.

Manuscript received on 12.09.2011

Julian Genov *was born in Varna, Bulgaria, on September 10, 1955. He studied at the Naval Academy "N. Vaptsarov "-Bulgaria and received MSc degree from the same academy in 1989. Since 1985 he worked in the Faculty of Transport of the Technical University of Sofia as Assistant Professor in the field of Mechanics. His field of interest includes vehicle dynamics, active control systems and wind turbines modeling.*

Contacts:
Faculty of Transport, Technical University – Sofia
e-mail: j_genov@mail.bg

Gancho Venkov *was born in 1937. He has graduated from the Technical University Sofia, Electro faculty, subject Electrical engineer (1963). He is associated professor in Faculty of Applied Mathematics and Informatics at the Technical University Sofia. His researches are in: mathematical modeling, neural networks and numerical methods.*

Contacts:
FPMI, Technical University – Sofia
e-mail: giv@tu-sofia.bg

Bogdan Gilev *was born in 1967. He has graduated from the Technical University Sofia, Electro faculty, subject Electrical engineer (1992) and Shumen University "St. Konstantin Preslavski", Faculty of Mathematics and Informatics, subject Higher Mathematics (1994). He has defended a PhD thesis in the Technical University Sofia (2010). He is assistant professor in Faculty of Applied Mathematics and Informatics at the Technical University Sofia. His researches are in: mathematical modeling, neural networks and optimal control theory.*

Contacts:
FPMI, Technical University – Sofia
e-mail:b_gilev@tu-sofia.bg