Simulation Model of Two-Rotor Wind Turbine with Counter-Rotation

Azhumakan Zhamalovich Zhamalov, Alaibek Dzhumabekovich Obozov,
Sapar Auezbekovich Issaev, Murat Merkebekovich Kunelbayev and
Laura Serikovna Baikadamova

[1]Kazakh State Women Pedagogical University, Almaty, Kazakhstan
[2]Kazakh State Teacher Training University, Almaty, Kazakhstan

Abstract: This paper deals with MATLAB Simulink simulation software package used for the description of operating regimes of disc generator with constant magnets for two-rotor wind turbine with counter-rotation, used in low power wind-driven power plants (WDPP). The results have shown that at high wind speeds, while maintaining a constant angular rate of windwheel (WW), the power generated by WW decreases. The developed model allows obtaining mechanical and energy characteristics for various wind speeds at given certain wind-driven power plant (WDPP) design parameters, as well as the optimum combination of the blade pitch, rotational rate, load torque and the control law that ensures highest power efficiency of wind energy utilization.

Key words: Wind · Imitation modeling · MATLAB Simulink · Two rotor wind turbine with counter-rotation

INTRODUCTION

Present-day power industry is experiencing a period of rapid development and anticipating for the inevitable change. Increase in energy consumption occurs against exhaustion and high prices of oil, the world's main resource which provides nearly 40% of world consumption. In the current contest, a tendency of increasing the share of renewable energy sources (RES), which are an alternative to traditional energy technologies, is evidenced all over the world.

Renewable energy sources are currently between 15% and 20% of total world energy consumption [1]. The wind energy conversion is a fast-growing interdisciplinary field comprised of multiple developments in science and technology. According to the American Wind Energy Association (AWEA), the average wind energy quota target increases by 29% per year [2]. At the end of 2009, the installed capacity of wind power worldwide was more than 159 MW. Projected wind energy for 2010 amounted to more than 203 MW [3]. Wind energy market has grown because of the environmental benefits of clean energy and thanks to the economic incentives provided by several governments [4].

Since 2010, simulation package Matlab Simulink includes the software for dynamic systems simulation.

The wind power plant systems are an example of a dynamic system, which contains subsystems with different range of time constants such as wind, turbine, generator, as well as electronics, transformer and grid components [5]. Dynamic modeling of wind machines and its linearization has been obtained by means of PID controller, which was used to adjust the speed of the turbine rotor and thus frequency regulation. In the proposed variable speed controller, the actuator and the turbine linear model was solved by the Matlab Simulink software package [6].

The Main Part: One of the main tasks when developing methodic basis and design of low power WDPP for autonomous wireless devices, marine buoys, shepherd homes and other low-power consumers in remote areas, is the development of a WDPP simulation model to determine the wind turbine energy generation depending on the main WDPP parameters and wind conditions.

In research and development of wind power engineering, physical and mathematical models are widely used, because full-scale experiments are not always possible for both technical and economic reasons. The mathematical model describes the real object with a certain degree of approximation (specification). The type of the model depends both on the studied object nature

and the research objectives, modeling techniques and the required accuracy. It is generally accepted that the mathematical modeling can be divided into three main types: analytical, simulation and combined modeling [7, 8]. A characteristic feature of the analytical modeling is description of the functioning elements of the modeled system in forms of certain correlations such as differential, integral-differential and finite-difference equations or logical conditions. The analytical model can be analyzed by the following methods [9, 10]: a) the analytical method (aiming at obtaining the various dependencies for the desired parameters in a general form), b) the numerical method (in this case, the goal is to obtain numerical results for certain initial data, without searching for a general solution); c) the qualitative method (certain system properties can be estimated without having the exact solution to the problem).

The development of modern computer technology gave us an opportunity to carry out a fairly accurate simulation of various systems using numerical methods. This significantly reduces the cost of the direct experiment, as many model parameters are specified during the computer simulation. Besides, there are certain problems, which cannot be solved based on direct experimentation on an actual model because this is impossible or economically unjustified.

Pivotal element of the WDPP is a windwheel (WW), which is characterized by power-speed coefficient:

$$z = R_{ww} \cdot \omega / V, \qquad (1)$$

where:
R_{WW} is windwheel radius;
ω is angular velocity;
V is wind speed.

The possibility of raising the windwheel rotation frequency is limited due to aerodynamic factors: the use of gearboxes and other mechanical equipment for this purpose is impractical because of the additional energy losses. Therefore, in recent years, multipolar generators with permanent magnets are used for these purposes. They are simple in design, reliable and do not require additional power for excitation windings. Operating modes of multipolar generator with permanent magnets, used in low capacity WDPP, are described in [5] using the MATLAB Simulink simulation software package. Using this mathematical model, the authors were able to describe adequately the stationary and transient operation modes of WDPP.
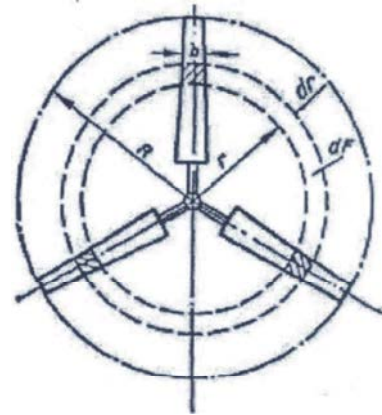

Fig. 1: Torque determination of the elementary blade WW

According to Fig. 1.14, the torque relative to the elementary WW axis is [11]:

$$dM = dQr = 4\pi r^2 \, dr\rho \times e(1+e)V^2(1 - \mu z_u)/(z_u + \mu), \qquad (2)$$

where:
dQ Is force member;
e - Drag factor of wind flow;
ρ - Air density;
V - Incident flow velocity;
Z_u - Relative number of modules (according to G.H. Sabinin);
μ - Drug-lift ratio of the blade (according to G.H. Sabinin);
b - Blade width;
dF - Elementary area;

Total torque of the WW is obtained by integrating this equation between r_0 and R:

$$M = \int_{r_0}^{R} dM = \int_{r_0}^{R} 4\pi r^2 dr\rho.e(1+e)V^2(1 - \mu z_u)/(z_u + \mu) \qquad (3)$$

where:
r_0 is the distance from the rotation axis to the blade tip.

For the mechanical power generated by the WW, it may be written:

$$N = w. \, M = 2\rho nM \qquad (4)$$

where:
ω is angular rotation frequency;
n is rotation frequency.

For the net power on the WW shaft we can write:

$$M_w = N_1/\omega = N \qquad (5)$$

where:

$$N_1 = N - \Delta N_W - \Delta N_P - N_{SWR} \qquad (6)$$

and

ΔN_w is blade clearance losses;
ΔN_p is blade profile losses;
N_{SWR} is losses caused by flow swirling behind the WW.

The equation of WW motion can be written as:

$$M_w - M_r = J \, (d\omega/dt), \qquad (7)$$

where:

$$M_r = M_F + M_L \qquad (8)$$

and M_F is frictional torque, M_L is load torque to WW shaft created by generator.

In most cases the modern modeling tools allow for providing a high level of model adequacy. Simulink is one of such tools. It is interactive tool for modeling, simulation and analysis of dynamic systems, which allows construction of graphical block diagrams, simulation of dynamic systems, investigation of the systems efficiency and project improvement. Simulink is fully integrated with the MATLAB application software package, providing access to a wide range of tools for analysis and design.

It is known that the energy generated by WDPP is proportional to the energy of the air flow. Specific power of the wind flow per surface unit perpendicular to the flow W can be represented as follows [12]:

$$W = \frac{1}{2}\rho v^3 \qquad (9)$$

where:
ρ is average density of air ($\rho = 1{,}225 \text{ kg/m}^3$ at T = 16°C);
v is average wind speed, m/s.

The mechanical energy of WW rotation W_M is determined by the power efficiency of wind energy utilization K_{WEU}:

$$K_{WEU} = \frac{w_m}{w}. \qquad (10)$$

The maximum energy that can be obtained from the ideal WW is about 59% of the air flow kinetic energy (Betz-Zhukovsky law), i.e. $K_{WEU} = 0.59$. For an actual WDPP with a horizontal axis of rotation, the values are within the range 0.1-0.47 [13].

To estimate the power, generated by the WW, the simulation model has been developed. The model includes two variable parameters: wind speed v and WW radius R. Process modeling diagram is shown in Figure 2.

A simulation was conducted using the MATLAB Simulink software package. The dependence K_{WEU} (v) is implemented in form of Lookup Table block and represents actually tabulated function, as well as independent input variables (air temperature, tower height and the installed capacity). The model developed by means of Simulink is shown in Figure 3.

To make it user friendly, the blocks of the diagram have different colors. Technical characteristics of WDPP are recorded in the green blocks, while climatic characteristics are indicated in the gray blocks. Output blocks also have different colors: blocks with a current value of generated power are pink, daily energy output of WDPP is shown in ultramarine blocks and the data available for export into spreadsheet for further processing is indicated in brown blocks.

Each calculated block is provided with the subsystem. Such implementation of the model makes it possible to avoid exerting the user's attention. Modular organization of the subsystem also facilitates debugging and reconstructing the model. The blocks used in the subsystem can be divided into three main types: blocks that accomplish the basic formulas; blocks that accomplish logic functions and blocks that represent variables.

The obtained results have shown that at high wind speeds, while maintaining a constant angular speed of WW rotation, power, generated by the WDPP, decreases. Usually this fact is not taken into account when assessing the medium-power WDPPs.

Obtained simulation data are used to construct *P (v)* dependence (WW radii were equal to 2.5, 3.5 and 5 m) (Figure 4).
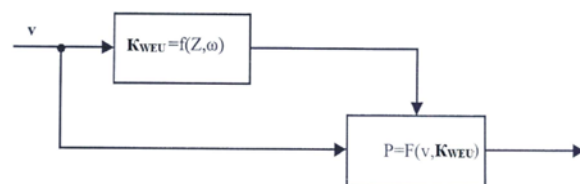

Fig. 2: WDPP simulation model diagram for obtaining $P = f\,(v)$ correlation
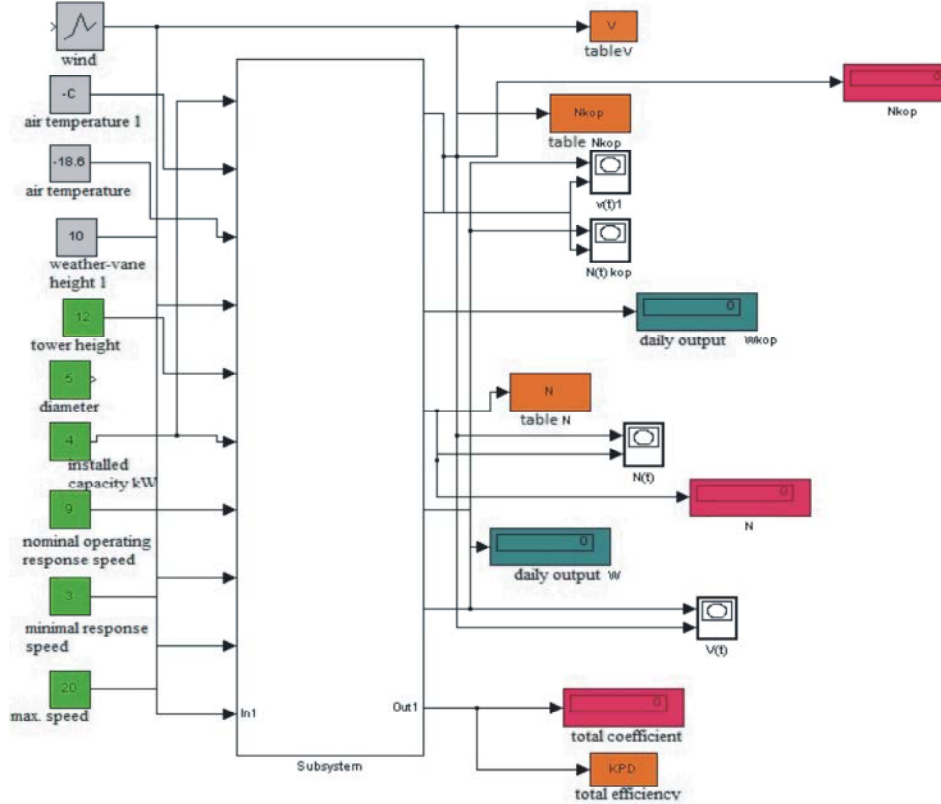
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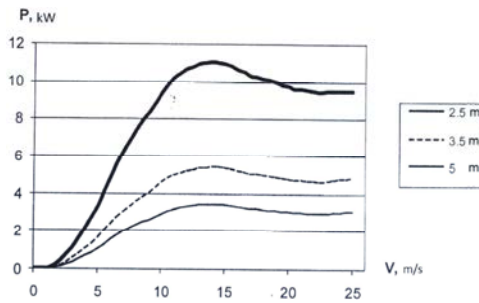Fig. 3: Simulation model of two-rotor wind turbine with counter-rotation

Fig. 4: The relationship between the WW shaft power, wind speed and WW radius at the constant rotation speed
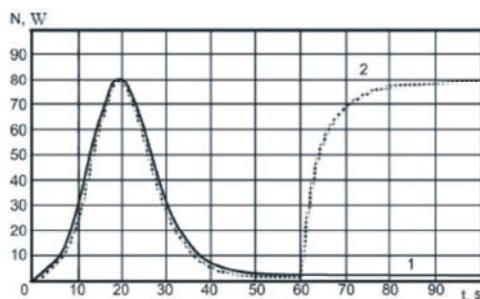

Fig. 5: Transient processes when running at idle and loading at a time point t = 60 s

CONCLUSION

The developed model allows obtaining mechanical and energy characteristics for various wind speeds at given certain WDPP design parameters, as well as the optimum combination of the blade pitch, rotational rate, load torque and the control law that ensures highest power efficiency of wind energy utilization.

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