MSC 28A50

MODELLING OF WIND TURBINE PERFORMANCE MEASUREMENT

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Wind turbines become more and more popular worldwide recently as any other renewable energy sources, therefore evaluation of specific turbine efficiency is a significant scientific and technical scope. Direct comparison of a number of performance measurements in general is not correct because of the versatile nature of a real wind. In permanently varying wind conditions the rotational speed is changing greatly causing the appropriate variety spectrum of generating power. The goal of our research was to study a ways of calculation of wind turbine efficiency and performance characteristics based on parameter information received in real wind conditions. Modeling of wind turbine operation was made using Matlab/Simulink software. Modeling showed the importance of the scope and proved its worthiness. Per our opinion the presented paper will be useful for turbine efficiency analysis and would help in the development of methodology for measurement and comparison of different turbines operating in real wind conditions.

Keywords: renewable energy, wind power, turbine performance, mathematical modeling, efficiency.

Introduction

Wind power utilization becomes more and more valuable, various types of wind turbines appear on the World market presenting diverse technical solutions intended on the improvement of performance which in turn should be evaluated. Surely the specific design could be tested in real wind conditions but the further comparison of testing data is not so easy as it could be imagined at once. The reason is the unstable wind speed caused by versatile nature of real wind flow giving different yield under different conditions for the same turbines. Therefore we see the demand of technique for correcting the interpretation of testing results based on data taken in real wind conditions [1].

We recognize the main characteristic of turbine as the efficiency also called power coefficient i.e. a ratio between generated mechanical power and aerodynamic power of wind flow across the swept area of wind turbine rotor.

Our research was focused in the exploration of capability of measuring the wind turbine efficiency in real conditions when the wind speed is changing continually.

1. Windmill model description

Mathematical model of turbine was developed for power coefficient defined in advance as known. The model contains the following equations:

$$J_t \frac{d\omega}{dt} = M_{\text{air}} - M_{\text{load}}, \tag{1}$$

where J_t – inertia of wind turbine; M_{air} – aerodynamic torque; M_{load} – load torque. (1) – basic differential equation, describing the rotation of wind turbine.

Aerodynamic torque:

$$M_{\text{air}} = C_P(Z)\frac{\rho V^2}{2}SR, \tag{2}$$

where $c_P(\lambda)$ – power coefficient (depends on tip speed ratio Z); ρ – air density; V – wind speed; S – swept area;R – radius of turbine.

Power coefficient $C_P(\lambda)$ depending on tip speed ratio Z could be approximated

$$C_P(Z) = (\frac{C_1}{Z} - C_2)e^{-\frac{C_3}{Z}} + C_4, \tag{3}$$

where C_1, C_2, C_3, C_4 – constants, Z – tip speed ratio:

$$Z = \frac{\omega R}{V}, \tag{4}$$

where ω – angular speed.

Characteristic of $C_P(Z)$ is shown on figure 1.

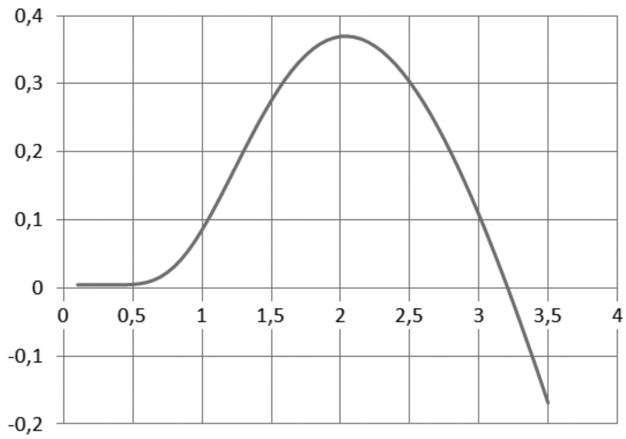

Fig. 1. Power coefficient C_P versus tip speed ratio Z

Torque of load:

$$M_{\text{load}} = \frac{P_{\text{м}}}{\omega}, \tag{5}$$

where $P_{\text{м}}$ – mechanical power of the alternator shaft.

Based on $C_P(Z)$ dependence we were able to find the dependence of aerodynamic power on wind speed and rotation speed [2].

Diagram demonstrating aerodynamic power versus wind speed and rotational speed is shown on figure 2. Based on this diagram we can declare that for each given wind speed value there is a rotational speed where mechanical power of wind turbine is maximal.

Mathematical model of alternator consists of the following equations:

$$P_{\text{phase}} = \frac{P_{\text{м}}}{3}, \tag{6}$$

(6) – electric power in alternator for one phase.

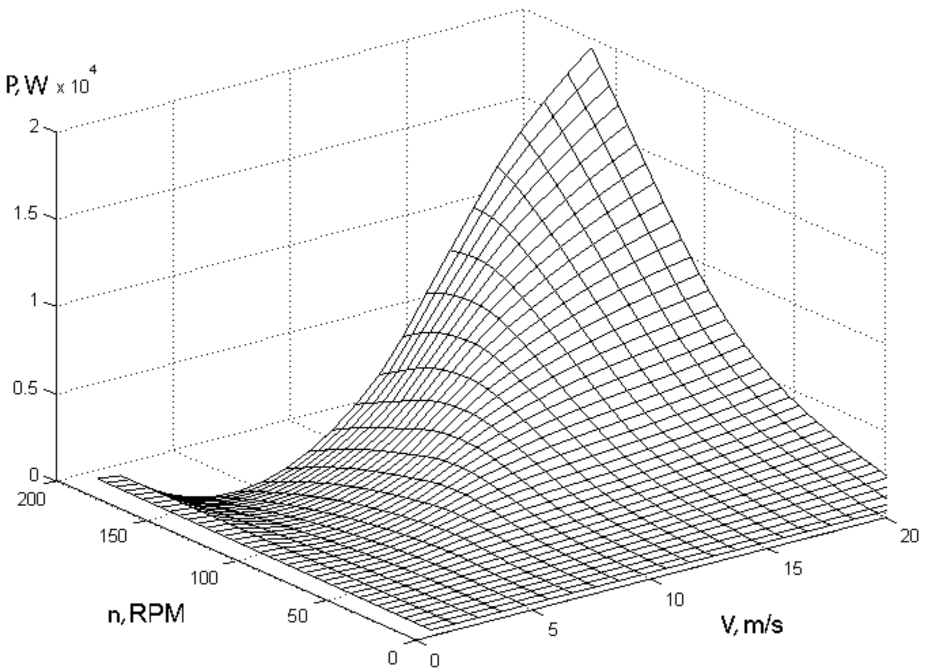

Fig. 2. Distribution of aerodynamic power according to wind speed and rotation speed

EMF in the phase is proportional to rotational speed:

$$E_{\text{phase}} = \omega k_1, \tag{7}$$

where k_1 is a constant.

Current in phase:

$$I_{\text{phase}} = \frac{P_{\text{phase}}}{E_{\text{phase}}}. \tag{8}$$

Then the losses in winding:

$$P_{\text{losses}} = I_{\text{phase}}^2 R_{\text{phase}}, \tag{9}$$

and losses in alternator:

$$P_{\text{losses total}} = 3 I_{\text{phase}}^2 R_{\text{phase}}, \tag{10}$$

where R_{phase} is the winding resistance.

Voltage on winding terminals:

$$V_{\text{phase}} = E_{\text{phase}} - R_{\text{phase}} I_{\text{phase}}. \tag{11}$$

"Star"connection of coils and bridge rectifier makes output voltage:

$$V_{\text{out}} = 2,34 V_{\text{phase}} \tag{12}$$

and output power:

$$P_{\text{out}} = P_{\text{м}} - P_{\text{losses total}}. \tag{13}$$

Rectifier output is connected to power converter, which adjusts the current in alternator changing load impedance so that the tip speed ratio Z provides maximum power coefficient C_P at current wind speed V. At the same time the whole of electric power P_{out} flows to the battery of infinite capacity. For better testing evaluation the mathematical model of wind turbine was realized in Matlab/Simulink software [3]. General view of the model is presented on figure 3.

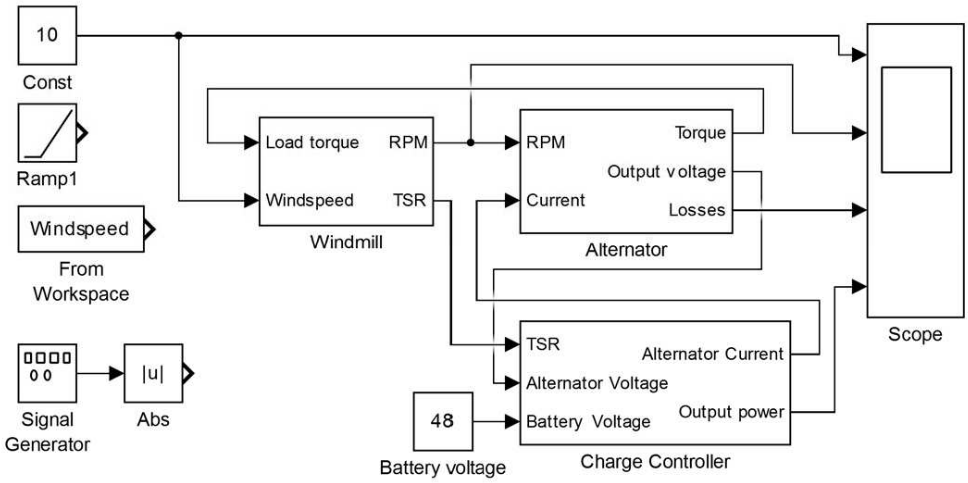

Fig. 3. General view of wind turbine Matlab/Simulink model

The model was tested using different signal generators simulating wind speed source, and finally adjusted for further research procedures [4].

2. Measurement of windmill performance

Next stage of the research was to analyze the developed model for applying different methods of efficiency measurement.

It was assumed as working hypothesis that the direct measurement of instantaneous wind speed and output power in real wind conditions for calculation of power coefficient C_P is correct. The result of these calculations is presented on figure 4.

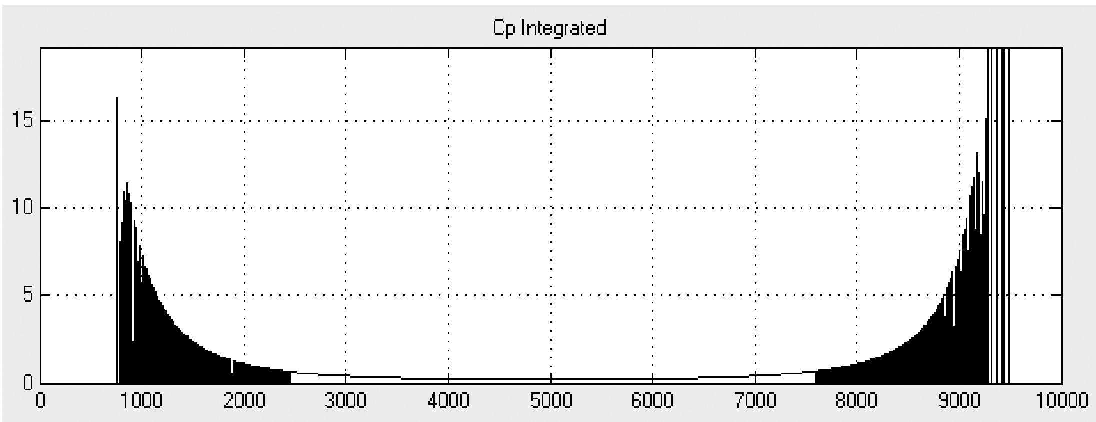

Fig. 4. Calculation of C_P based on current values of measured parameters

Diagram shows that power coefficient C_P differs from the expected values. This fact can be explained by processes in power controller of wind turbine which are changing the output power according to special algorithm providing the maximum yield [5].

Thereby to get the adequate numbers we had to use two different algorithms of processing the measured data.

The first algorithm is based on the processing of the numbers using the low-pass filter.

Second algorithm controls the integrating of the weighted values of C_P in time. Contribution of C_P should be proportional to output power, and average value is as follows:

$$C_P = \frac{\sum (P_{\text{out}}(i) C_P(i))}{\sum P_{\text{out}}(i)} \quad (14)$$

where $P_{\text{out}}(i)$ – current output power, $C_P(i)$ – current coefficient of power.

Measuring diagram in Matlab/Simulink is shown on figure 5.

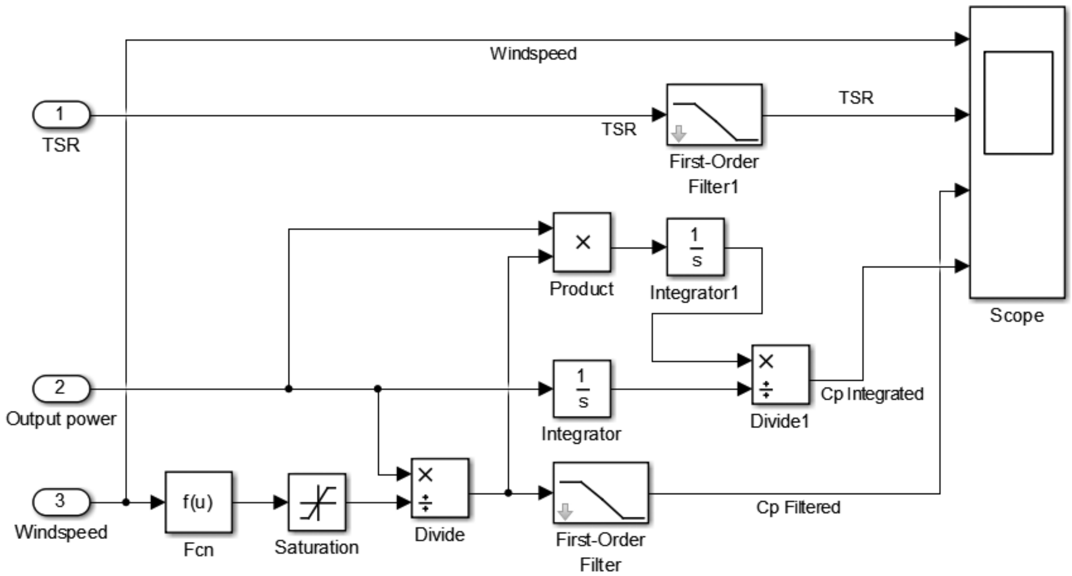

Fig. 5. Diagram of C_P calculation in Matlab/Simulink

Experimental model was affected by periodically variable wind speed shown on figure 6.

Power coefficient C_P curve at periodically variable wind speed for both methods is shown on figure 7. From diagrams on fig. 7 it is obvious that both methods help to increase the precision of power coefficient value comparing to the defined by model. The difference between two methods is in accuracy of numbers. First method works better with the big number of short-time wind speed fluctuations. The second one is more suitable for the stable wind speed conditions and provides more accuracy at long-term testing.

The model was also tested by samples of real wind speed values collected during the field testing (fig. 8).

Power coefficient C_P at a sampled wind speed is shown on figure 9.

Diagram shows the difference from previous results. It can be explained with the following arguments: inertia of wind turbine does not allow adjusting the rotational speed in time [6]. The research showed that the task of determination of power coefficient in real operating conditions does not have a simple solution; therefore there is a demand

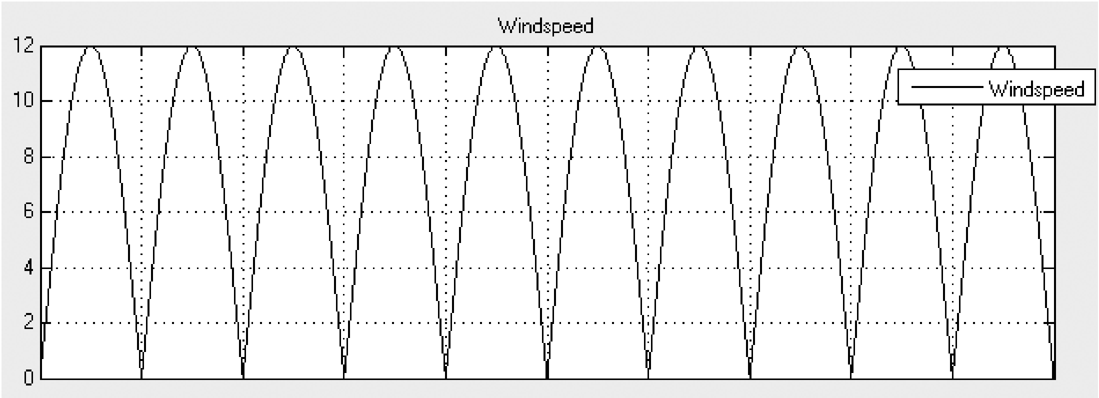

Fig. 6. Periodically variable wind speed

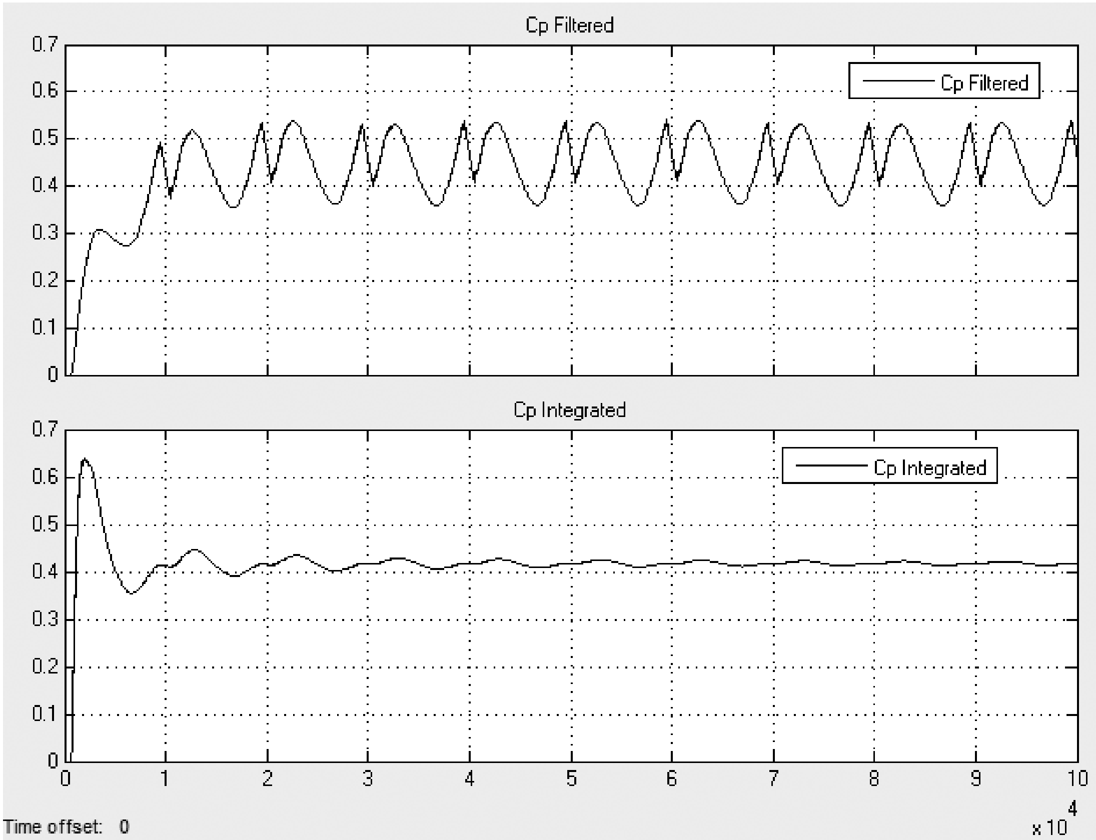

Fig. 7. Power coefficient C_P at periodically variable wind speed for both methods

for special techniques of measuring the efficiency of turbine using the wind speed and generated power samples.

Conclusions

Based on the research we could make the following conclusions:

1. Calculation of power coefficient based on current wind speed and generated power is limited in practice by the stability of parameters collected during measurement.

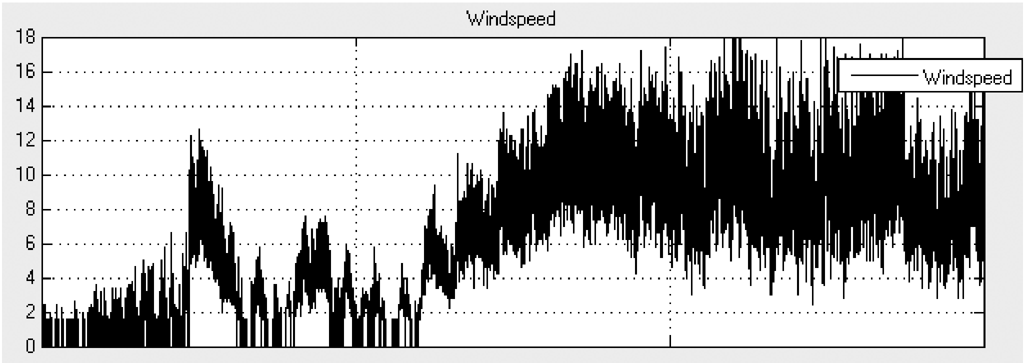

Fig. 8. Real wind speed recorded in the field

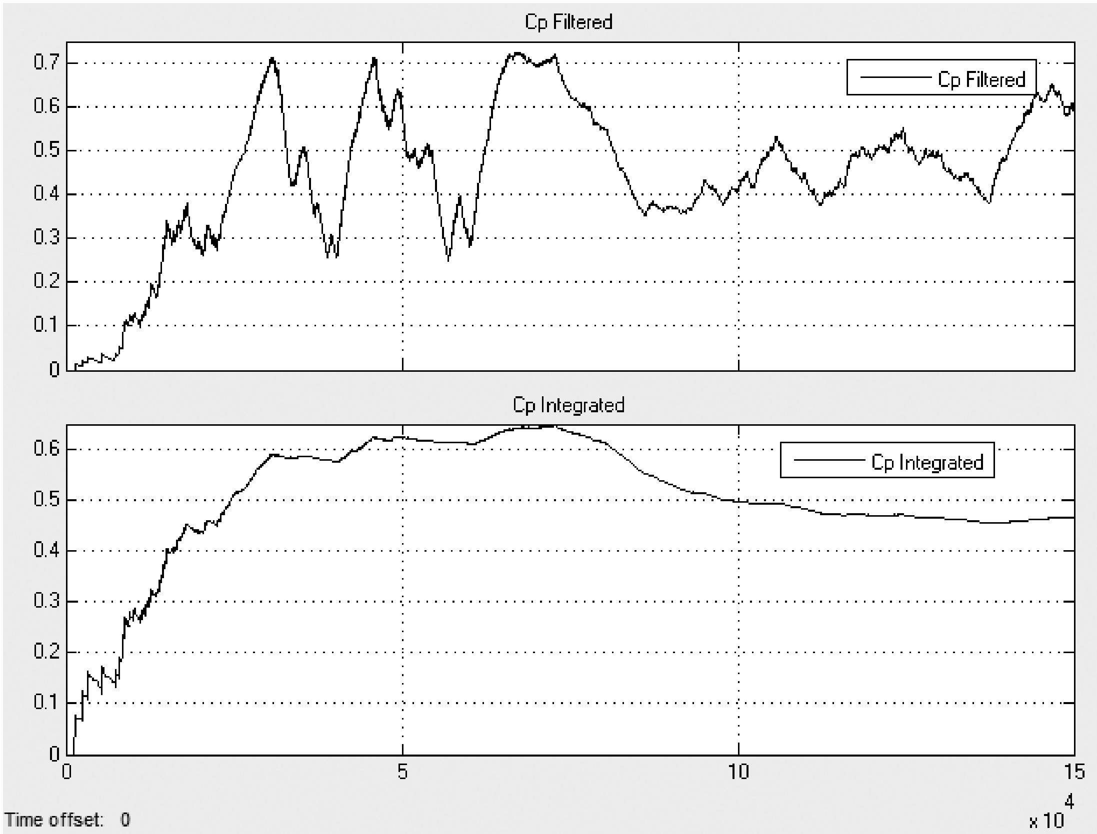

Fig. 9. Calculated power coefficient C_P at sampled wind speed

2. Calculating the C_P based on current wind speed and generated power it is important to take into account not just current but also previous values.

3. There is a bunch of reasons introduced above showing a necessity for the development of methodology for measurement of performance characteristics of wind turbines in real wind conditions.

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References

1. Eggleston D.M., Stoddard, F.S. *Wind Turbine Engineering Design*. New York, NY: Van Nostrand Reinhold, 1987.

2. Pao L.Y., Johnson K.E., A Tutorial and the Dynamics and Control of Wind Turbines and Wind Farms. *The American Control Conference*. St. Louis, MO, June 2009, pp. 2076–2089. DOI 10.1109/ACC.2009.5160195

3. Pronin N.V., Martianov A.C., Solomin E.V. Development of a mathematical model of wind turbine output capacity 3 kW produced by "SRC-Vertical"in the MATLAB package. *International Scientific Journal "Alternative energy and ecology"(ISJAEE)*, 2011, no. 5, pp. 41–44. (in Russian)

4. Martyanov A.S. [Power control in the windmill]. *Nauchnyj poisk: materialy tret'ej nauchnoj konferentsii aspirantov i doktorantov. Tekhnicheskie nauki.* [*Scientific research: third conference of post graduate students*]. Chelyabinsk, Publishing Center of SUSU, 2011, vol. 2, pp. 206–209. (in Russian)

5. Johnson K.E., Pao L.Y., Balas M.J., Fingersh L.J. Control of Variable-speed Wind Turbines: Standard and Adaptive Techniques for Maximizing Energy Capture. *IEEE Control Systems Magazine*, 2006, no. 26(3), pp. 70–81.

6. Drouilhet S., Muljadi E., Holz R., Gevorgian V. Optimizing Small Wind Turbine Performance in Battery Charging Applications. *Windpower 95 Conference*. Washington, DC, March 27-30, 1995, 13 pages, available at: http://www.nrel.gov/docs/legosti/old/7808.pdf

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