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Comparative analysis of wind turbine control strategies

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Abstract

An article describes a comparative analysis of windmill control strategies based on computer modelling in Matlab/Simulink software. For the research purposes, the mathematical windmill model we developed consisted of a wind turbine, an electric generator, an electric power converter, and an accumulator battery. The main feature of the proposed model is the universal charge controller module operating under the control of different algorithms written in a high-level programming language. The model imitates three different control strategies. The main comparative criterion of windmill efficiency is the power coefficient, i.e. the ratio of the generated electric power to the aerodynamic wind power. The testing setup was equipped with a windmill controller developed for operation under the control program that supports different control strategies. Results showed the best control strategy is to maintain the optimal tip-speed ratio, and all the results can now be applied to other types of wind turbines.

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Keywords: renewable energy, wind turbines, wind generation systems, control strategies, variable speed control, power optimization.

1. Introduction

At the present time, because of ecological problems and due to limitation of natural energy sources the renewable energy becomes widespread and more popular competing with gas and oil energy extracting technologies. Concerning the renewable energy sources, the most developing technology is the wind energy. Modern wind turbine stations and windmill farms compiles the complex system for electricity generation [21]. And research and investigation of such systems is not possible without modern mathematical theory operating on powerful computers and calculation clusters [5]. Usually this problem can be solved by numeric methods in mathematics [19] with the help of proper software operating on high-speed computers [11].

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In wind energy industry during the developing of constructions, aerodynamic and mechanical properties there is a demand on improvement of operation control in a wide range of wind speed [1]. Many well-known researchers published their results about windmill speed control [1, 2, 3, 6, 7, 15, 16] in order to improve the efficiency of electric energy generation. Thus, the task of improvement of wind turbine efficiency by using the optimal control strategy is important part of scientific problem of renewable energy cost reduction [20].

Main reason to use the different wind turbines control strategies is the fact that the wind speed varies in time and the rotation speed of wind turbine should follow the wind speed in order to extract the maximum power [4]. Now there are several basic control strategies of windmill what are wide-speared:

– working at the constant rotation speed of wind turbine in a wide range of wind speed [17];
– working at step-fixed rotation speed of wind turbine in order to expand the wind speed range where the windmill operates with maximum efficiency [18];
– working at variable rotation speed of wind turbine in order to cover the whole wind speed range with maximum efficiency [1].

Main criteria for comparing of the strategies described above is a coefficient of power – ratio between generated electric power and aerodynamic power of wind [10]. Therefore, the task of research is to compare the coefficient of power obtained for different control strategies in wide range of wind speed.

2. Materials and Methods

The research was focused on measurement of wind turbine efficiency at different wind speed. Assumed that the mathematical model of wind turbine has power coefficient defined in advance as known [13]. The model contains the following equations. The main differential equation, describing the rotation of wind turbine [18]:

$$J\frac{d\omega}{dt} = M_a - M_e, \tag{1}$$

where J – inertia of wind turbine; ω – angular speed; M_a – aerodynamic torque; M_e – load torque.

Aerodynamic torque is:

$$M_a = C_P(Z)\frac{\rho \cdot S \cdot V^3}{2 \cdot \omega}, \tag{2}$$

where $C_P(Z)$ – power coefficient (depends on tip speed ratio Z); ρ – air density; V – wind speed; S – swept area.

Power coefficient $C_P(Z)$ is approximated by:

$$C_P(Z) = (\frac{c_1}{Z} - c_2) \cdot e^{(-\frac{c_3}{Z})} + c_4, \tag{3}$$

where $c_1 \ldots c_4$ – constants, tip speed ratio Z is:

$$Z = \frac{\omega \cdot r}{V} \tag{4}$$

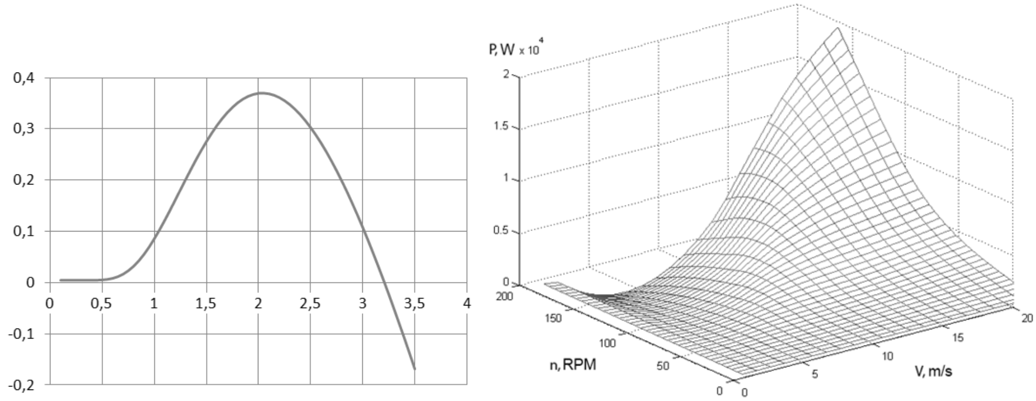
where r – radius of turbine.

The mechanical power of wind turbine is:

$$P_a = C_P(Z)\frac{\rho \cdot S \cdot V^3}{2}, \quad (5)$$

where $P_м$ – mechanical power of the alternator shaft.

Characteristic of $C_P(Z)$ is shown on figure 1(a). Based on $C_P(Z)$ dependence we found the dependence of aerodynamic power on wind speed and rotational speed. Diagram demonstrating aerodynamic power versus wind speed and rotational speed is shown on figure 2 (b). 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 [7].



a) b)

Fig. 1 Power coefficient versus tip speed ratio (a) and distribution of aerodynamic power according to wind speed and rotational speed (b).

Mathematical model of electric generator consists of the following equations. Voltage for one phase:

$$u = e - r \cdot i - L\frac{di}{dt}. \quad (6)$$

EMF in the phase is proportional to rotational speed:

$$\begin{cases} e_A = k \cdot \omega \cdot \sin(2p \cdot \omega \cdot t), \\ e_B = k \cdot \omega \cdot \sin(2p \cdot \omega \cdot t + \frac{2\pi}{3}), \\ e_C = k \cdot \omega \cdot \sin(2p \cdot \omega \cdot t - \frac{2\pi}{3}). \end{cases} \quad (7)$$

where k is a constant.

Output voltage after “star” connection is:

$$u_{AB} = u_A + u_B; u_{BC} = u_B + u_C; u_{CA} = u_C + u_A \quad (8)$$

Three phase rectifier bridge forms output voltage by:

$$u_{out} = max(|u_{AB}|,|u_{BC}|,|u_{CA}|)\,, \tag{9}$$

and electromagnetic torque of alternator is [9]:

$$M_e = \frac{u_{out} \cdot i_l}{\omega} \tag{10}$$

where i_l is the current of load.

Rectifier output is connected to power converter, which adjusts the current in alternator changing load impedance according to the modelling strategy [12]. For simulation the mathematical model of wind turbine was realized in Matlab/Simulink software. Diagram of wind turbine model and simulation setup is presented on figure 2.

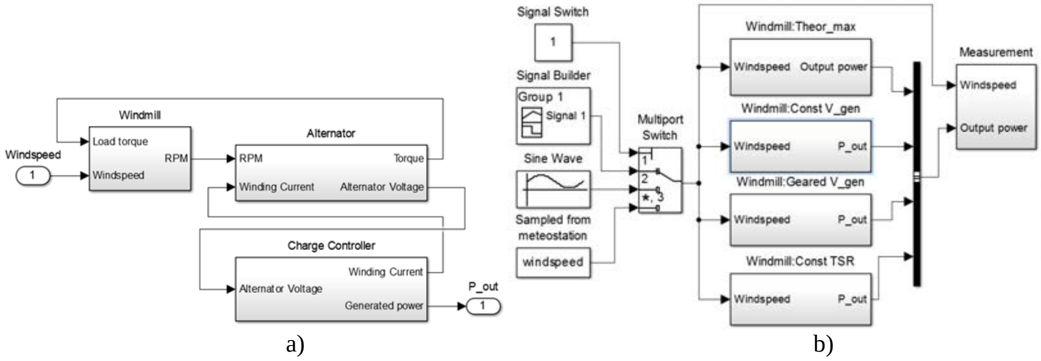


Fig. 2. Diagram of wind turbine model (a) and simulation setup (b) in Matlab/Simulink software.

Simulation setup consist of four modules of wind turbines named “Windmill:... ” where each module operates according to its own control strategy defined by algorithm described on high-level programming language in block “s-function” of Simulink. Module “Windmill:Theor_max” defines the maximum possible power at the given wind speed for the given wind turbine. Module “Windmill:Const V_gen” defines the operation of windmill with constant turbine speed where alternator shaft directly attached to the wind turbine. Module “Windmill:Geared V_gen” defines the operation of windmill with variable turbine speed and constant alternator speed provided by mechanical transmission with variable transfer ratio. Module “Windmill:Const TSR” defines the operation of windmill with variable turbine speed and constant tip speed ratio provided by alternator operating at variable speed. All the wind turbine models were affected by several wind speed influences [14]:

1. Linear increasing wind speed.
2. Periodic sine wave wind speed.
3. Sampled real wind speed recorded using anemometer in the field.

Each wind turbine module consist of three basic parts:

– «Windmill» – subsystem, providing conversion of driving torque from wind speed, its diagram presented on figure 3.
– «Alternator» – subsystem that converts the mechanical power to electric output, see figure 4(a).
– «Charge Controller» – subsystem for determining the wind turbine control strategy, figure 4(b).

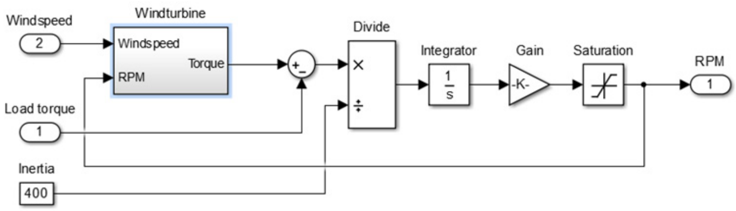
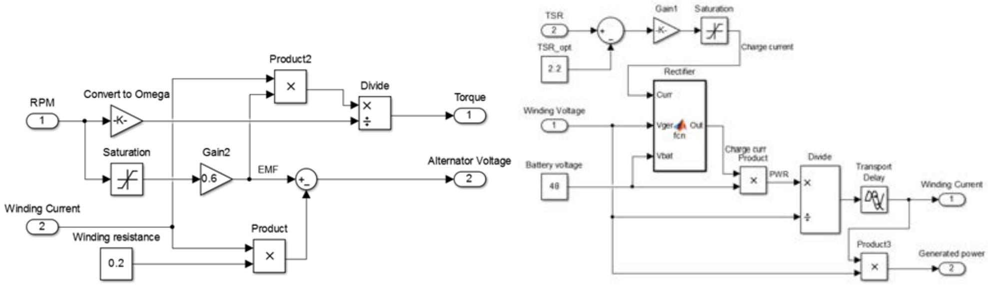


Fig. 3. Diagrams of «Windmill» subsystem for conversion of driving torque from wind speed.



a) b)

Fig. 4. Diagrams of subsystem for conversion of mechanical power to electric output (a) and subsystem for determining the wind turbine control strategy (b).

Wind turbine control strategy using mechanical transmission with variable ratio needs additional subsystem for imitation of gearbox [13]. This subsystem converts the rotation speed and transferred torque according to given transfer ratio and should be located between wind turbine and alternator subsystems. Diagram of gearbox subsystem is shown on figure 5.

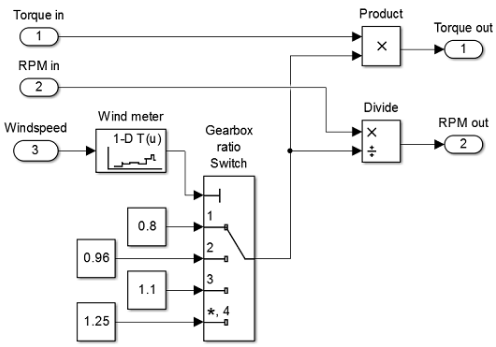


Figure 5 – Diagram of gearbox subsystem.

For measurement of the wind turbine efficiency at the variable wind speed the module "Measurement" was developed. Module provides the integrating of weighted values of C_P in time [8]. Contribution of C_P should be proportional to output power, and average value is as follows:

$$C_{Pintegr} = \frac{\sum (Pe_i \cdot Cp_i)}{\sum Pa_i} \tag{11}$$

where Pe_i – current output power; Pa_i – current coefficient of power; n – number of samples.

3. Results

Simulation with linear increasing wind speed demonstrates the efficiency of each strategy in whole range of wind speed where wind speed is changing slowly (fig. 6).

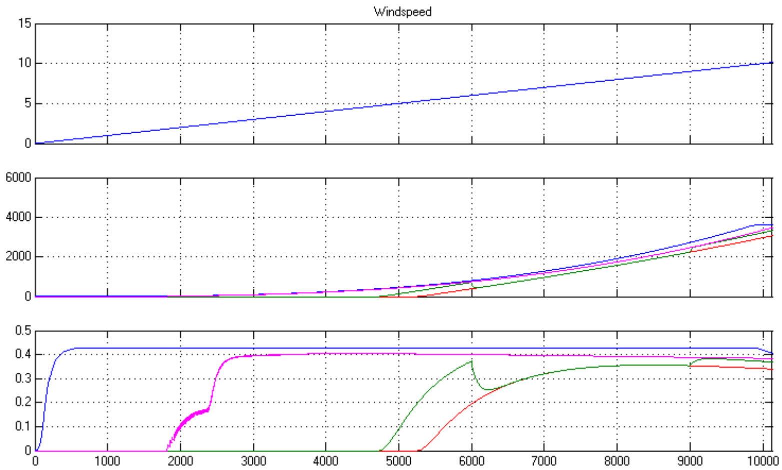


Fig. 6. Results of simulation with linear increasing wind speed.

Top diagram of figure 6 shows the wind speed in simulation time. Next one shows the generated electric power: blue line indicates the maximum possible power limited by defined coefficient of power in the turbine model. Red line shows the output power for constant speed wind turbine; green line demonstrates operation with gearbox. Purple line indicates the output power for variable speed wind turbine with variable speed alternator. Bottom diagram shows real coefficient of power calculated according to generated electric power at given wind speed. All line colors are similar to the lines described above. The testing shows that using gearbox can improve the efficiency of wind turbine that operates at wide range of wind speed comparing to operating with constant turbine speed. Moreover, the most effective strategy is the operation at variable speed of wind turbine with variable speed alternator.

Next test is the simulation of wind turbine models under sine wave wind speed influence, fig. 7. This testing demonstrate stability of operation for all control strategies. In addition, similar to previous testing the best operation strategy is for variable speed of wind turbine and electric generator.

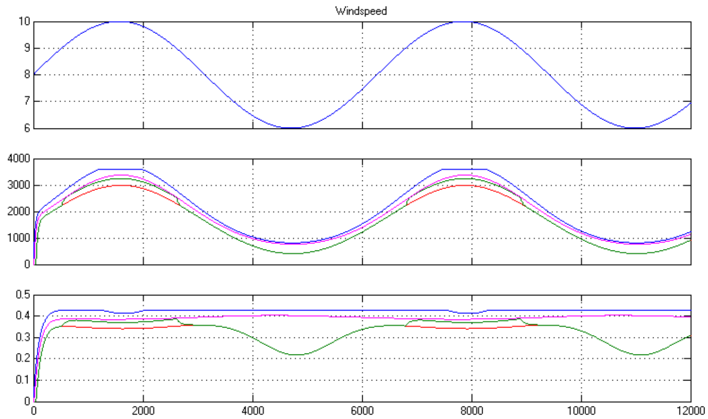


Fig. 7. Model response on periodic sine wave wind speed.

And final testing with sampled real wind speed shows the advantage of control strategy where wind turbine operates at variable speed and constant tip speed ratio, see figure 8.

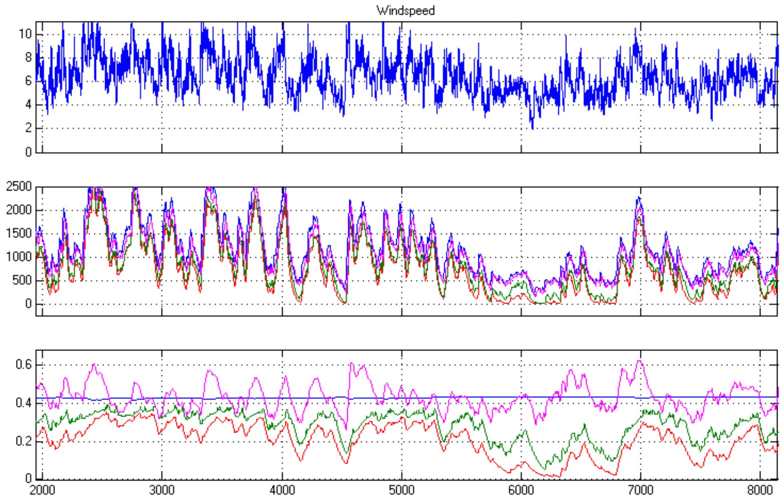


Fig. 8. Results of simulation with sampled real wind speed.

On the bottom diagram of figure 8 we can see that sometime the coefficient of power for constant TSR strategy is more than theoretical maximum. This fluctuation around mean value is normal because average value does not exceed the maximum limit. Fluctuation of coefficient of power occurs when the wind speed changes and control system tries to adjust the tip speed ratio. At that time the wind turbine starts to collect the wind energy in kinetic energy of rotation and later gives it back to alternator, so the is a time shift between wind energy extraction and generated energy utilization.

Conclusions

According to fulfilled research the results demonstrate the importance of choosing the proper strategy for given wind conditions. When the windmill location has a regular wind speed then the wind turbine can be designing for operations at constant wind turbine speed. This approach can reduce the cost of generated power because the constant speed windmills cheaper. However, if there is a task to extract maximum energy from the wind in a wide range of wind speed, the best solution is to use the windmill operating with variable wind turbine speed at constant tip speed ratio.

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References

[1] B. Boukhezzar, H. Siguerdidjane, Maureen Hand M, Nonlinear control of variable-speed wind turbines for generator torque limiting and power optimization. ASME Transactions, Journal of Solar Energy Engineering. 128(4) (2006) 516–30.
[2] E.F. Camacho, Bordons C, Model predictive control, Springer, UK, 1999.
[3] P.W. Carlin, S. Laxson, E.B. Muljadi, The history and state of the art of variable-speed wind turbine technology, Report NREL/TP–500–28607, National Renewable Energy Laboratory, U.S.A, 2001.
[4] R. Datta, V.T. Ranganathan, Method of tracking the peak power points for a variable speed wind energy conversion system, IEEE Transactions on Energy Conversion. 18(1) (2003) 163–168.
[5] J. Espinosa, J. Vandewalle, V. Wertz, Fuzzy logic, identification and predictive control, Springer, UK, 2005.
[6] Jianzhong Zhang, Ming Cheng, Zhe Chen, Xiaofan Fu, Pitch Angle Control for Variable Speed Wind Turbines, DRPT2008. (2008).
[7] K.E. Johnson, L.Y. Pao, M.J. Balas, L.J. Fingersh, Control of variable-speed wind turbines: standard and adaptive techniques for maximizing energy capture, IEEE Control Systems Magazine. 26(3) (2006) 70–81.

[8] A. Kusiak, Dynamic control of wind turbines, Renewable Energy. (2009). DOI:10.1016/j.renene.2009.05.022
[9] A.S. Martyanov, Generator of Turbine Engine Power Station, Eastern European Scientific Journal. 5 (2014) 202–206.
[10] A.S. Martyanov, E.V. Solomin, Modelling of Wind Turbine Performance Measurement, Journal of Computational and Engineering Mathematics. 2 (2014) 18–25.
[11] N.V. Pronin, A.S. Mart'yanov, E.V. Solomin, Razrabotka matematicheskoy modeli vetroenergeticheskoy ustanovki moshchnost'yu 3 kVt proizvodstva OOO «GRTs-Vertikal' v pakete Matlab, Al'ternativnaya energetika i ekologiya, NIIES. 5 (2011) 41–44.
[12] A.S. Mart'yanov, E.V. Solomin, Kontroller zaryada vetroenergeticheskoy ustanovki, Mezhdunarodnyy nauchnyy zhurnal «Al'ternativnaya energetika i ekologiya». 1(81) (2010) 106–109.
[13] A.S. Mart'yanov, Regulirovanie moshchnosti v vetroenergeticheskoy ustanovke, Nauchnyy poisk: materialy tret'ey nauchnoy konferentsii aspirantov i doktorantov. Tekhnicheskie nauki, Chelyabinsk, Izdatel'skiy tsentr YuUrGU. 2 (2011) 206–209.
[14] I.M. Kirpichnikova, A.S. Mart'yanov, E.V. Solomin, Modelirovanie generatora vetroenergeticheskoy ustanovki, Elektrotekhnika. 10 (2013) 46–49.
[15] S. Morimoto, H. Nakayama, M. Sanada, Y. Takeda, Sensorless output maximization control for variable-speed wind generation system using IPMSG, IEEE Transactions on Industry Applications. 41(1) (2005) 60–7.
[16] E.B. Muhando, T. Senjyu, N. Urasaki, A. Yona, T. Funabashi, Robust predictive control of variable-speed wind turbine generator by self-tuning regulator, In: IEEE Power Engineering Society General Meeting. (2007) 1–8.
[17] N. Nanayakkara, M. Nakamura, H. Hatazaki, Predictive control of wind turbines in small power systems at high turbulent wind speeds, Control Engineering Practice. 5(8) (1997) 1063–9.
[18] P. Novak, T. Ekelund, Modelling, identification and control of a variable speed HAWT, In Proceedings of the European Wind Energy Conference. (1994) 441–446.
[19] Y.D. Song, B. Dhinakaran, X.Y. Bao, Variable speed control of wind turbines using nonlinear and adaptive algorithms, Journal of Wind Engineering and Industrial Aerodynamics. 5(3) (2000) 293–308.
[20] E. Torres, M.Garcia-Sanz, Experimental results of the variable speed, direct drive multipole synchronous wind turbine, TWT1650, Wind Energy. 7 (2004) 109–118.
[21] Y.C. Zhu, Multivariable system identification for process control, Pergamon Press, New York, 2001.