Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 129 (2015) 640 – 646

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on Industrial Engineering

Adaptive control over the permanent characteristics of a wind turbine

Solomin E.V.*, Sirotkin E.A., Martyanov A.S.

South Ural State University, 76, Lenin Avenue, Chelyabinsk, 454080, Russian Federation

Abstract

Herein is proposed a system for adaptive speed control of the permanent characteristics of a wind turbine to ensure safe operation thereof. The design of wind turbines is generally calculated with the nominal power generation at a wind speed of 11 m/s, and it should be controlled at higher wind flow velocities. Rotation speed is the main control parameter of wind turbine system. In addition, the control system can provide normalized thermal conditions for the alternator and prevents exceeding vibration level. Adaptive control system contains mechanical and electromechanical modules intended for braking rotor using friction components. There is also a structure diagram of control system and transfer functions of system components.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the organizing committee of the International Conference on Industrial Engineering (ICIE-2015)

Keywords: wind energy; control system; adaptive control; centrifugal brakes.

1. Introduction

Wind energy is well known and being utilized for a long time. During the last few centuries we saw a technology development in wind industry, as results we can find more and more wind turbines (WT) converting the kinetic energy of airflow into electric power (in some cases into mechanical one) [1]. Wind turbine companies are seeking for a different ways of the product cost reduction [2] including the wind turbines weight decrease. However, such lightweight constructions are not intended for a longtime operation in heavy duties and may fail [3]. Sometimes WTs are optimized to generate a maximum of energy in the most probable wind speeds (as a usual 11 m/s, but may vary

* Corresponding author. Tel.: +7-912-317-18-05;
E-mail address: e.solomin@bk.ru

1877-7058 © 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the organizing committee of the International Conference on Industrial Engineering (ICIE-2015)
doi:10.1016/j.proeng.2015.12.084

up to 25 m/s) [4]. Showing the nominal wind speed higher is a trick of sales managers to show higher performance, because well known that the higher wind speed is more rarely observed in the continental areas [5]. Meanwhile, often there is a demand for control of WT on the high winds. Otherwise, the rotor of WT may be destroyed, mechanical transmission can be damaged, and alternator may overheat [6]. Also, one of the dangerous factors in WT operation is the vibration generating by a construction as a result of resonances on several frequencies, as a rule. The vibration effect leads to the increase of radial flapping, bearing failure, reduction of lifetime, basement concrete cracking. All these negative effects lead to the damage of WT and increase the danger during its usage [7].

2. Adaptive control system

We propose the adaptive control system as the way to provide the safe usage of wind turbine. The feature of this system is the control of wind turbine reaction. Since the control system is proposed initially to provide the safety operation, the main controlled parameters are the technical state of the wind turbine. In case of rotor failure caused over speed rotation, the turbine parts with high kinetic energy may damage the surroundings objects so the most important controlled parameter of wind turbine is rotation speed. The control of other characteristics (temperature of alternator [8]) can be taken into account as secondary or dependent on the primary values. There are many different modifications and variants of wind turbine design. Let's focus the discussion on centrifugal cam braking system for Vertical Axis Wind Turbine (VAWT), presented in Fig. 1. However, it is possible to spread this design for any WT type because almost each wind turbine contains such components as rotor shaft, mast, housing, etc. [9].

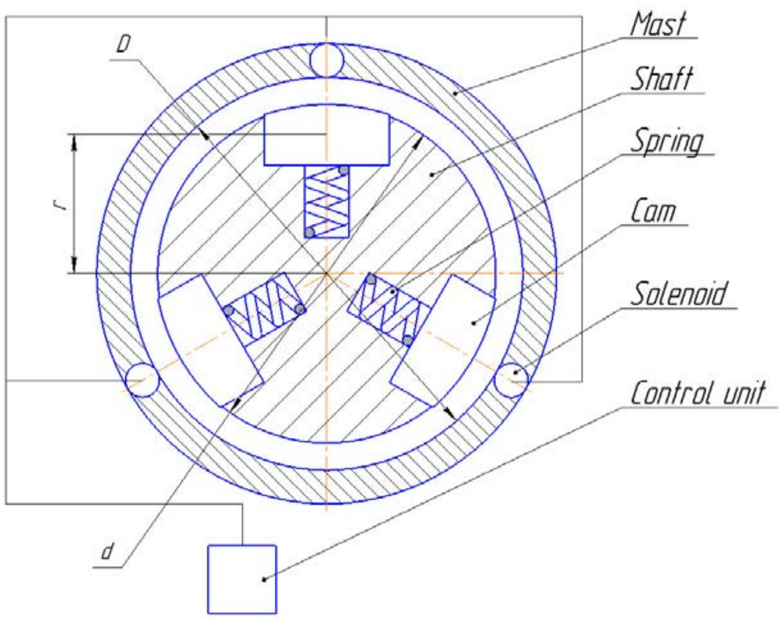

Fig. 1. Design of centrifugal cam device of mechanical action.

When the rotor rotation frequency is above zero *($\omega > 0$)* the centrifugal force F_c all geometrical points of rotating rotor (excluding those on the rotation axis). Its value is in proportion with the square of rotation frequency:

$$F_c = mr\omega^2, \quad (1)$$

where m – mass of rotating element, r – distance from rotation axis to the center of mass of this section.

The cam moves in the slot along the radial direction, being connected with the shaft by a spring keeping cam moving from the slot. The spring stretching l can be calculated according to Hooke's law in relative form [10]:

$$l = \frac{F_{sp} L}{ES}, \quad (2)$$

where F_{sp} –stretching force of spring on the length l, L – length of spring, S – cross-section wire, E – Young modulus.

To move the cam from its initial position, the following condition is required:

$$F_{sp} < F_c. \quad (3)$$

In this case, the centrifugal force exceeds the elastic force and the cam gets moving from the center. However, this condition is not enough for the cam to contact a friction surface of the internal wall of mast starting the rotor braking. The determined value of angular velocity should correspond the determined value of centrifugal force acting on the cam. Thus the cam should cover the distance equal to the difference of outside radius of the cam and internal radius of the mast wall $l = D - d$. Reaching of distance l the cam touches the internal mast wall and start sliding along its surface.

Friction force in this case depends on support reaction force N_{normal}, and on the coefficient of friction for contacting surfaces in accordance with the following equation [11]:

$$\left| F_{fr} \right| \le \mu N_{normal}. \quad (4)$$

Note that the friction coefficient depends also on the sliding speed. However, this dependence is quite small and the μ could be a constant when the high accuracy of measurement is not required [12].

Air flow affects the rotor of WT making a rotating torque. Applying a contrary acting torque by the brake reduces rotation speed [13]. Taking into account the inertia of rotor, the braking process can considered as long in time that increases the failure probability. It is also known that the pressure on the blades has a wavy impact (as the wind gusts have a jumping type characteristic), and the system reaction speed should be relatively high to provide the safety operation in time [14]. Thus, it is necessary to generate a friction torque M_{fr} exceeding the torque generated by wind flow M_w to handle a braking process during a short time [13]:

$$M_{fr} = F_{fr} \frac{D}{2} > M_w. \quad (5)$$

Apparently, having high rotation speed the cams may transfer the whole rotating torque. The value of this rotating torque M_{fr} (friction torque), transferring by cams from the shaft to the mast, can be determined as follows [15]:

$$M_{fr} \le 0,5(F_c - F_{sp})\mu z D = 0,5 mrDz\mu(\omega_{\lim}^2 - \omega_0^2), \quad (6)$$

where z – number of friction parts (cams).

Thus, the braking cams press the mast walls on nominal rotation speed with a force, when the rotating torque of wind rotor is not enough for driving the cams and rotor stops. It is important that the momentary stop or rotor may cause the high impact loading on all construction components, especially on the blades, and the aggregate may fail.

In this case, it is necessary to determine the optimal position between two boundary states of the system. I.e. we need a fast acting centrifugal system to reduce the risk of accidents to a minimum, but the time for response cannot be zero, as it lead to the destruction of the structure due to the critical loads. This means that the cams should have a soft braking characteristic, and braking process should start before rotation reaches the extreme speed. Therefore, it is necessary to operate in a vary ω_o with limitation of the maximum speed by ω_{lim}. In the speed range between ω_o and ω_{lim} the cam touches the mast wall, but keep sliding reducing the torque and rotation speed. By reducing the rotation speed of the rotor shaft, the centrifugal force gets less and the cams pressure on the wall reduces. Fig. 2 is a graph of torque transmitted by the cams and rotor speed. Up to ω_o the rotor rotates without activating a braking system, then in accordance with the shaft speed coming to the range between ω_o and ω_{lim}, the system will be automatically activated by moving cams.

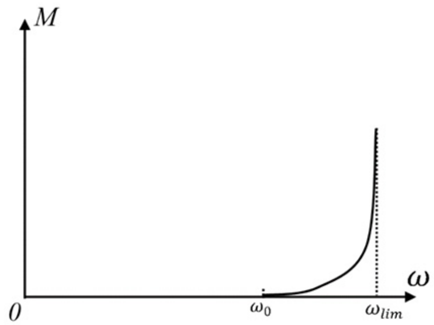

Fig. 2. A graph of the torque transmitted by the cam(s) and rotor speed of the wind rotor.

Such parameters as temperature of coils in the electric generator and the vibration depend on the rotation speed of the rotor [16]. One more feature of the adaptive control system is a possibility to monitor the abnormal temperature of the generator windings and vibration of the mast by respective sensors, and slow down or stop the turbine in the malfunction. In this case, some solenoids in the rotor shaft activate cams to stop rotation. The electric driven cam can touch the mast wall even in case when the rotation speed of rotor haven't reach ω_o value.

Solenoid should be activated by an electric signal from a smart control system, which will send control signals to solenoids. The cam touches the mast wall when magnetic field is strong enough to affect the cam and thereby stretch the spring, and the following condition should be true:

$$F_{act} > F_{sp}. \tag{7}$$

Process for getting a braking condition (5) requires the following:

$$F_{act} \geq 2\frac{M_w}{D}. \tag{8}$$

Thus, controller system of adaptive wind turbine control gets the information from three different sensors: temperature, vibration and shaft speed. Last sensor seems redundant, since the rotation speed is controlled by spring stretching characteristic independently on the control signal. However, in case of failure of any component of centrifugal cam system, the rotor will accelerate to nominal speed and the sensor can send the signal to the controller, which could eventually prevent the accident.

3. The control scheme

For quantitative analysis of the processes during the signal exchange between the components of the control system, it is advisable to represent the system in the form of block diagram. The block diagram (Fig. 3) is a schematic representation of the control system as a set of functional blocks, each of which has a certain transfer function [17].

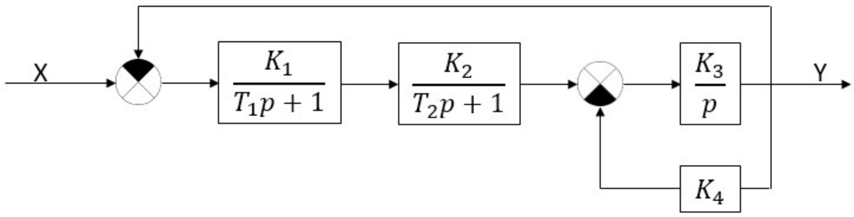

Fig. 3. Control system in a block diagram form.

The main regulating effect in the wind turbine control system (Fig. 4) is realized by pushing mechanism, which consists of solenoids and braking cams. The principle of control and adjustment is based on the control error compensation function. Control block diagram is shown in Fig. 5.

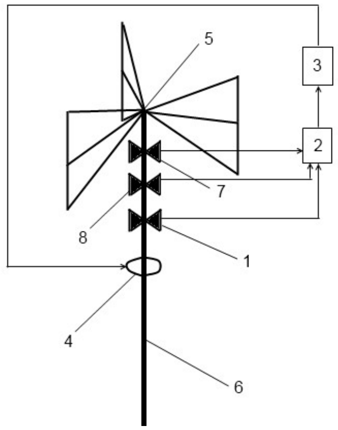

Fig. 4. adaptive control system of wind turbine: 1 – shaft ω speed sensor; 2 – comparing block; 3 – amplifier; 4 – pressing mechanism (solenoids) and moving cams; 5 – rotor; 6 – mast; 7 – alternator τ_g temperature sensor; 8 – vibration ψ sensor.

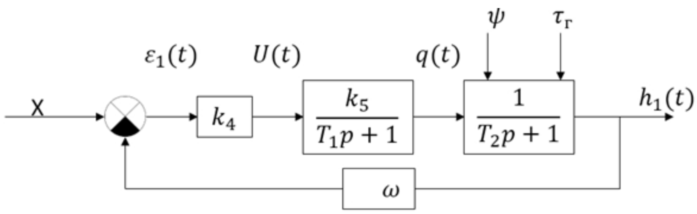

Fig. 5. Block diagram of wind turbine control system.

Since the temperature of the alternator windings τ_g and vibration levels ψ are determined by wind turbine rotor speed ω, the rotor rotation speed will be the major controlled parameter. The nominal value of the shaft speed h_1 is set up by sequential block as analog signal x_{task}. Information about current value of the controlled parameter $h_1(t)$ is obtained by the speed sensor and converted further into the signal $x(t)$, coordinated by referring to the signal x_{task}. Comparison of the set and the true values for the control parameter is in the comparator block. It generates the error signal $\varepsilon(t) = x_{task} – x(t)$. After the conversion required to obtain a signal suitable for testing by actuator, it implements the control action $U(t)$ on controlled object in the form of pressing the braking cams to the mast wall by solenoids in accordance with the magnitude and sign of the error $\varepsilon(t)$ [18].

Thus, the block diagram allows converting the quantitative dependences for cam motion estimation into the signal function to get a shaft speed distribution. Based on a spring rate and using formulas of elastic theory, the displacement of the cam is implemented into the contact with the mast wall to eliminate the deviation from the given value [19].

Transfer functions of system components:

- wind turbine speed sensor $W_1(p) = K_1$;
- converter (amplifier) $W_2(p) = K_2$;
- solenoids (actuators) $W_3(p) = K_3 / (T_1 p+1)$;
- braking cams (controlled object) $W_4(p)=1 / (T_2 p+1)$.

Specific values of coefficients K_i and time constants T_1 are defined by property of the equipment, and could be easily determined. If the controlled object and the control system are developing is at the same time, this allows getting the best combination of their characteristics. For instance, if the preliminary calculation indicates a lack of processing speed, then there is a number of possible solutions for this problem. Usage of high power solenoids is also possible. It will increase the dynamic response of the system and decrease the mass of braking cams, or reduce the spring stiffness. If characteristics of sensitivity or precision control are unsatisfactory, then these problems could be solved by increasing the gain in sensor blocks and converting the error signal, or interpose corrective links into the structure [20].

This work was supported in part by Ministry of Education and Science of Russian Federation under the project “Carrying out applied researches in the field of technology of high reliable energy saving systems for different purposes based on modern equipment of renewable and hybrid generation, accumulation, distribution and consuming of energy” according to the contract no. 14.577.21.0069 d.d. 05.06.2014, unique identifier RFMEFI57714X0069.

References

[1] I.M. Kirpichnikova, A.S. Martyanov, E.V. Solomin, Preobrazovanie energii v vetroenergeticheskih ustanovkah, Mezhdunarodnyiy nauchnyiy zhurnal «Alternativnaya energetika i ekologiya». 1 (2010) 93–97.

[2] E.V. Solomin, Vetroenergeticheskaya ekonomika, Mezhdunarodnyiy nauchnyiy zhurnal «Alternativnaya energetika i ekologiya». 2 (2010) 28–30.

[3] E.V. Solomin, I.M. Kirpichnikova, A.S. Martyanov, Iteratsionnyiy podhod v razrabotke i optimizatsii vertikalno-osevyih vetroenergeticheskih ustanovok, «Elektrotehnika. Elektrotehnologiya. Energetika», Sbornik nauchnyih trudov VII mezhdunarodnoy nauchnoy konferentsii molodyih uchenyih, Novosibirskiy gosudarstvennyiy tehnicheskiy universitet; Mezhvuzovskiy tsentr sodeystviya nauchnoy i innovatsionnoy deyatelnosti studentov i molodyih uchenyih Novosibirskoy oblasti. (2015) 92–95.

[4] E.V. Solomin, Vetroenergeticheskie ustanovki GRTs-Vertikal, Alternativnaya energetika i ekologiya -ISJAEE. 1 (2010) 10–15.

[5] P.P. Bezrukih, Ispolzovanie energii vetra. Tehnika, ekonomika, ekologiya, Kolos, Moscow, 2008.

[6] A.N. Kindryashov, A.S. Martyanov, E.V. Solomin, Elektricheskie mashinyi vetroenergeticheskih ustanovok s vertikalnoy osyu vrascheniya, Mezhdunarodnyiy nauchnyiy zhurnal «Alternativnaya energetika i ekologiya». 1/2(118) (2013) 59–62.

[7] I.M. Kirpichnikova, E.V. Solomin, Vibrogasiteli macht sverhmalyih vertikalno-osevyih vetroenergeticheskih ustanovok, Vestnik YuUrGU. Seriya «Energetika», Izd-vo YuUrGU. 13-14(190) (2010) 78–81.

[8] I.M. Kirpichnikova, A.S. Martyanov, E.V. Solomin, Modelirovanie generatora vetroenergeticheskoy ustanovki, Elektrotehnika. 10 (2013) 46–50.

[9] P.P. Bezrukih, P.P. Bezrukih (mladshiy), Vetroenergetika. Vyimyislyi i faktyi. Otvetyi na 100 voprosov, Institut ustoychivogo razvitiya Obschestvennoy palatyi Rossiyskoy Federatsii, Tsentr ekologicheskoy politiki Rossii, Moscow, 2011.

[10] Gorshkov, Troshin, Shalashilin, Soprotivlenie materialov, second ed., 2005.

[11] F.P. Bowden, D. Tabor, The Friction and Lubrication of Solids, Oxford University Press, 2001.

[12] Bo N.J. Persson, Sliding Friction, Physical Principles and Applications. Springer, 2002.
[13] E.V. Solomin, I.M. Kirpichnikova, E.A. Sirotkin, RF Patent 142083 (2013).
[14] V.M. Lyather, Razvitie vetroenergetiki, Malaya energetika. 1-2(4-5) (2006) 18–38.
[15] G.P. Tarikov, A.T. Belskiy, V.V. Komrakov, Detali mashin : ucheb. posobie, M-vo obrazovaniya Resp. Belarus, Gomel. gos. tehn. un-t im. P. O. Suhogo, Gomel: GGTU im. P. O. Suhogo, 2010.
[16] E.A. Sirotkin, A.S. Anikin, S.V. Kozlov, E.E. Solomin, Regulirovanie chastotyi vrascheniya rotora vertikalno-osevoy vetroenergeticheskoy ustanovki, Mezhdunarodnyiy nauchnyiy zhurnal Alternativnaya energetika i ekologiya. 5(145) (2014) 32–36.
[17] I.M. Makarov, I.M. Lohin, S.V. Manko, M.P. Romanov, Iskusstvennyiy intellekt i intellektualnyie sistemyi upravleniya, Nauka, Moscow, 2006.
[18] V.G. Ilichev, Proektirovanie sistema avtomaticheskogo upravleniya, Izd-vo: YuUrGU, Chelyabinsk. 2001.
[19] I.D. ZolotarYov, V.V. Valikov, RaschYot dinamicheskih rezhimov kolebatelnyih sistem spetsialnogo vida: uchebnoe posobie, Izd-vo: OMGU, 2009.
[20] Bianchi, D. Fernando, Wind turbine control systems: principles, modelling and gain scheduling design, 2007.