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Investigation of a Rotor Speed Controlling of a Promising Wind-Driven Power Plant Using Several Variable Elements of its Geometry

Abstract

Variants of the rotation frequency stabilization of a promising vertically axial wind-driven power plant consisting of a doubly connected stator and a rotor with blades are considered. The stator as a whole is part of the construction, axisymmetric with the rotor, and the rotor is slightly buried in the upper part of the stator — the bell. This plant can be included as an element in a complex power plant for additional and emergency power supply of both stationary and mobile objects, for example, surface robotic systems. The paper proposes to use an aerodynamic method of the rotor angular speed stabilization by controlling the positions of two variable design elements of the plant with respect to its stator. As such elements, a lower guide structure (one of the stator elements) and an aerodynamic brake flap can be used. The rearrangement of both elements positions relative to the stator changes the effective cross section for the interaction of the wind flow entering the installation with the rotor. The method of controller synthesis by the angular speed of the rotor rotation is considered in detail. A feature of this controller is the presence of two control channels with one state variable. First, it is necessary to determine the dynamic ranges of torque control on the rotor shaft for each of the variable geometry elements. This allows to correctly select the switching condition between the two control channels depending on the degree of deviation of the desired flow rate from the current speed. Based on the second-order control error equation, the desired control law of the angular rotor speed is obtained. Using the example of the problem solving of angular speed stabilization with given quality criteria, we simulated a synthesized control system for various initial data. It is shown that the constructed controller is capable of effectively countering the influence of wind disturbances in a wide range of deviations of the current speed from the frequency desired for a given target value.

Keywords: *vortex type wind-driven power plant, aerodynamic torque, variable geometry elements, regulation error equation, reduced disturbance observers, rotation frequency stabilization*

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Исследование регулирования частоты вращения ротора перспективной ветроэнергетической установки с использованием нескольких переменных элементов ее геометрии

Рассматриваются варианты стабилизации частоты вращения ротора перспективной вертикально-осевой ветроэнергетической установки, состоящей из двусвязного статора и ротора с лопастями. Статор в целом является осесимметричной с ротором частью конструкции, а ротор немного заглублен в верхнюю часть статора — раструб. Эта установка может входить в качестве элемента в комплексную силовую энергетическую установку для дополнительного и аварийного электропитания как стационарных, так мобильных объектов, например, надводных робототехнических комплексов. В работе предлагается использовать аэродинамический метод стабилизации угловой скорости вращения ротора путем управления положениями двух изменяемых элементов конструкции рассматриваемой установки относительно ее статора. В качестве таких элементов могут быть использованы нижняя направляющая структура — один из элементов статора, и аэродинамическая тормозная заслонка. Перестроение положений обоих элементов относительно статора изменяет эффективное сечение взаимодействия входящего в установку ветрового потока с ротором. Подробно рассмотрена методика синтеза регулятора угловой скорости вращения ротора. Особенностью этого регулятора является наличие двух каналов управления при одной переменной состояния. Вначале необходимо определить динамические диапазоны регулирования крутящего момента на валу ротора для каждого из изменяемых элементов геометрии. Это позволяет корректно выбрать условие переключения между двумя каналами управления в зависимости от степени отклонения желаемой скорости потока от текущей скорости. На основании уравнения ошибки регулирования второго порядка и процедуры синтеза редуцированных наблюдателей возмущений вращающего момента получен искомый закон управления угловой скоростью вращения ротора. На примере решения задачи стабилизации угловой скорости с заданными критериями качества проведено моделирование синтезированной системы управления при различных исходных данных. Показано, что построенный регулятор способен эффективно парировать влияние ветровых возмущений в широком диапазоне отклонений текущей скорости от желаемой для данного целевого значения частоты.

Ключевые слова: *вихревая ветроэнергетическая установка, аэродинамический крутящий момент, изменяемые элементы геометрии, уравнение ошибки регулирования, редуцированные наблюдатели возмущений, стабилизация частоты вращения*

Introduction

Currently, there is a large group of facilities, stationary-based and mobile, including robotic systems, in need of auxiliary autonomous energy sources.

For example, many international companies are developing and implementing alternative energy sources on marine surface platforms to reduce their total fuel consumption is carried out by [1, 2].

One of the approaches that allows economically tangible (more than 10 %) to reduce the consumption of conventional fuel is the use of a complex power plant (CPP), consisting of a wind-driven power plant (WP) and a solar power plant.

The key problems in this case are: 1) to choose a WP type, suitable for installation on a stationary/mobile platform as an element of the CPP; 2) the development of CPP electromechanical control system, allowing to optimize its operation according to the criterion of maximum power generated under severe restrictions imposed by the safety requirements and reliability of operation of all carrier systems [3].

Complex power plants can be used as a source elements that are part of a distributed electric network, providing a controlled transfer of energy from such sources to consumers — load elements. This transmission occurs under conditions of perturbations of these elements, various external influences on the network, and, as a result, various modes of its operation, including emergency ones. For stability and robustness of the control system of such distributed power system, strict restrictions must be imposed not only on the upper level of this control, which is responsible for the correct assessment of the characteristic electrical quantities of the system and control of the key state variables of the sources, receivers and transmission lines themselves [4]. Big demands must be made on the local control systems of source elements. The last requirements are reduced, firstly, to coordinated work with the upper level of control and, secondly, to sufficiently accurate stabilization of the characteristic output values of these sources in accordance with the specified current operating mode of the entire system.

This article discusses problem of WP rotor angular speed stabilization due to the regulation of the aerodynamic properties of this plant.

Such regulation in the general case can be carried out using variable geometry elements (VGE) of WP construction [5—7].

A variable geometry element of the horizontally axial WP construction, as a rule, is the total angle of their blades installation. A striking example here is a 600 kW guided modernized research turbine (CART2) operated by the National Renewable Energy Laboratory (NREL), pc. Colorado. The rotor speed controller of this WP takes into account both turbulent wind disturbances and significant parametric uncertainties of the rotor motion model with a maximum value of 20 % [5]. These uncertainties are caused, first of all, by the blades considerable flexibility of modern WP, as well as by the mass variability and inertia characteristics of the rotor, generator and the corresponding error in their estimation, which increase with increasing diameter of the rotor. The paper [6] analyzes a much simpler controller that controls the specified CART2 plant for a number of modes with almost the same quality of work.

However, VGE using for vertically axial WP is currently very limited. Since, for example, the use of a wind wheel for this WP type with an adjustable angle of rotation relative to a certain axis will lead to more complex and much less predictable changes than in the case of a change in the overall pitch of the propeller of a horizontally axial WP. The reason for this is that the theory of the screw is much more studied than the aerodynamics of the corresponding rotors used for vertically axial plants. Nevertheless, publications are known where a controlled change in the aerodynamic properties of a vertically axial vortex type WP is considered by using a VGE located on the stator part of the installation [7].

For the vertically axial WP aerodynamic control of rotor speed at the present stage of drive mechanisms development as well as theoretical and computational dynamics of continuous media is additional to the existing electrical control. At the same time, controlling the aerodynamic properties of such WP can significantly reduce the requirements for a number of system elements for electric control of the generator frequency and amplitude, such as a rectifier, battery, inverter [8]. This becomes possible due to a significant reduction in the changes range in the speed and amplitude of the output signal of WP generator through such aerodynamic regulation.

The development of precision mechanics, including actuator drives of WP elements and the technology for manufacturing precision parts, together with an increase in the efficiency and depth of aerodynamic analysis of processes occurring during WP operation, can eventually make the method of angular speed aerodynamic control the main for some WP types, or, according to at least by backing up the existing stabilization method. The consequence of this development is the appearance in the future of two WP classes.

Installations can be attributed to the first, the design of which will allow more efficient control of the angular speed using the VGE. For example, for WP with high rated power, appropriate expensive equipment for electrical control is required. However, if there are sufficiently fast-acting VGE for some of them, it will become possible to completely eliminate a number of elements of the specified equipment.

The second class will include WP, the design of which will not allow the introduction of effective control using VGE. This may be due to the complexity of aerodynamic regulation by such VGE, which can lead, especially for low power plants, to the inefficiency of aerodynamic regulation according to the price / quality criterion.

For a number of WP with an increased demand for output characteristics and reliability of operation, both stabilization methods can be applied.

In the present work, the vertically axial vortex type WP with one VGE is taken as a basis [3, 7, 8]. The necessity of introducing an additional variable geometry element for the possibility of the rotor angular speed controlling in a wider dynamic range of wind loads is substantiated, and the corresponding modernized plants design is proposed. Next, the regulator of this control system is considered.

The design and operation principle of the original WP

The wind-driven power plant, which is taken as the basis [3, 7], contains a moving part — a rotor with blades, as well as a doubly connected part of the structure — a stator. The latter includes a bell, which is a vertical channel with the possibility of air passing inside it — a bell, and a lower guide structure made in the form of a cone-shaped rotation figure. The stator as a whole is axisymmetric with the rotor part of the structure, and the rotor is slightly buried in the socket (see Fig. 1, *a,* see the third side of covered).

The operation of a vortex type wind-driven power plant is based on the principle of useful aerodynamic interference between the static and rotor parts of the plant [7, 9—13], as well as the use of special-shaped rotor blades that effectively perceive both horizontal and vertical ascending flows [7, 13]. The vortex resulting from the rotor rotation is concentrated inside the diffuser and over its upper part. The formed areas of reduced pressure cause the additional traction effect — the average pressure in the lower part of the rotor (p_1) is much higher than the average pressure in its upper part, as well as above the edge of the upper part of the stator (p_2); this effect increases the rotor rotation moment. The vortex structure arising above the rotor additionally energizes the rotor, being in dynamic equilibrium with it (Fig. 1, *b,* see the third side of covered).

A possible application of considered WP [7] as a part of the complex power plant small displacement boats are shown in Fig. 1, *c* (see the third side of covered), and as a part of a wind power station of several combined WP, in Fig. 1, *d* (see the third side of covered).

In works [3, 7], the aerodynamic advantages of such plant are shown, both in terms of the generated power and in terms of minimizing the noise level, in comparison with analogues [13—19]. The design of this plant was obtained as a result of aerodynamic optimization according to the criterion of maximum torque on WP rotor shaft.

A need for modernization of the aerodynamic control system of the angular speed of WP rotor

Consider the problem of the rotor rotational speed controlling of a vertically axial vortex type WP, described above (Fig. 1, *a*, see the third side of covered).

The position of the stator, lower movable part, characterized by the h magnitude, can vary vertically relative to the rotor (Fig. 1, *b,* see the third side of covered). Therefore, this part of the stator is a variable element of WP geometry [3, 7]. Deviation of the position of this element leads to a change in the aerodynamic properties of the plant. By adjusting the value h depending on the wind load, which is within certain limits, it is possible to stabilize the rotor angular speed ω, if the dependence of the rotor aerodynamic moment on the wind speed, angular speed and on [7] is known.

However, stabilization ω in the entire range of wind loads using the value h considered in [7] is not possible, since the dynamic range of the change in the rotor aerodynamic moment due to the change in value h is not sufficient to achieve this goal.

In this paper, we consider a system for controlling the rotor angular speed ω using two variable geometry elements of the plant design: the lower guide structure and the aerodynamic brake flap. The combined use of these two VGEs makes it possible to increase the dynamic range in terms of the rotor aerodynamic moment so that it becomes possible to adjust ω for any average value of the wind load and arbitrary amplitude of the wind disturbance in a certain range of rates of change of this disturbance over time.

Fig. 2 (see the third side of covered) shows the principle of vortex type WP operation with an additional element on the construction — an aerodynamic brake flap (ABF). Such flap regulates the effective cross section of the incident wind flow interaction with the rotor in the range of values from the maximum — when the flap does not overlap the incident flow at all, to almost zero — when the flow is almost completely blocked, as a result of which the rotor rotation is slowed down. At the same time, it also generates significant turbulence, which complicates the aerodynamic analysis and its accuracy. To compensate for the inaccuracy of determining the moment on the rotor shaft at various ABF positions relative to the stator bell, a torque perturbation observer on the rotor shaft can be introduced into the developed control system. Thus, the proposed plant contains two VGEs, which are characterized by values h_1 and h_2.

Synthesis of a controller of a modernized vortex type WP with two VGEs

Lets perform synthesis of the regulator of the proposed WP. For such synthesis, it is necessary, first of all, to have a dependence $\omega_0 = f_0(V_0)$ of the steady-state value of the angular speed ω_0 on the unperturbed uniform wind flow speed V_0.

In the general case, the target value of the rotor rotation speed ω_g differs from ω_0 that corresponding to the current average wind speed V_0 without taking into account possible wind disturbances therefore, Automatic Control Sistem (ACS) with a VGE must not only fend off these disturbances, but also fend off the difference $V_{0g} - V_0$, where $V_{0g} = f_0^{-1}(\omega_g)$, f_0^{-1} — function inverse to f_0. Thus, it is necessary to fend off the difference $\Delta V(t) = V(t) - V_{0g}$ between the full free wind speed $V(t)$ and the desired value V_{0g}; we will proceed from the following law of change in the speed of the incoming air flow during gusts of wind:

$$V(t) = V^*(t) = \\ = V_0 + A_V \exp(\alpha_V t)\sin(\Omega_V t + \varphi_V), \quad (1)$$

where A_V— wind amplitude, α_V, Ω_V — constant parameters, one of which can be equal to zero; φ_V — initial phase of the process of increasing disturbance.

Now it is necessary to determine to what extent the difference $\Delta V(t)$ can vary in order to control the angular speed with a given quality.

We establish the required quality of the regulation process with the given parameters of the transient process $\Delta T_p'$ and degree of overshoot $\eta_\omega = \Delta\omega_{max}/\omega_g$ relative to the permissible $\Delta\omega_g$ deviation from the nominal target value ω_g. For example, let $\Delta\omega_g = 0{,}05\omega_g$, $\Delta T_p' = 5$ s, $\eta_\omega = 50$ %. Next, find out in which range the difference $V(t) - V_{0g}$ the control system considered in [7] is capable of stabilizing the angular speed ω with specified quality parameters. The analysis shows that such stabilization by means of VGE of the lower guide structure of the considered vortex type WP is possible at $\left|V(t) - V_{0g}\right|_{max} / V_{0g} \leqslant \delta_{1V\,max} = 0{,}3$. Here the case is admissible when $V(t) < V_{0g}$, if the nominal dependence $V_{0g} = f_0^{-1}(\omega_g)$ obtained for the normal intermediate position of the lower guide structure. Its deviation up from the indicated normal position, i.e. a decrease in the parameter h_1 (Fig. 1, *b*, Fig. 2, see the third side of covered) leads to an increase in the rotor torque, and a downward deviation leads to its decrease [3, 7].

The introduction of an additional VGE — ABF leads, as mentioned above, to the expansion of the upper limit of the allowable range in speed, therefore, in the end, the dynamic range of regulation of the flow rate for the developed ACS is:

$$-\delta_{V1\max}V_{0g} \leqslant V(t) - V_{0g} \leqslant V_{kr} - V_{0g}, \quad (2)$$

where V_{kr} the maximum allowable wind speed for the integrity of WP construstion and its functioning in normal mode; this speed, as a rule, is obviously greater than the upper limit of installation operating speed range.

Let the equation of WP controlled object is given, which is an equation of the rotational motion of its rotor with an angular speed ω:

$$J\frac{d\omega}{dt} = M(V, \omega, h_1, h_2) + M_c(\omega), \quad (3)$$

V — wind speed, the changes of which in this problem represent external disturbance; h_1, h_2 — control value of two VGEs determining their current position relative to the bell stator; J — reduced moment of the rotor inertia; $M(V, \omega, h_1, h_2)$ and $M_c(\omega)$ — useful aerodynamic moment on the rotor and moment of resistance, determined by the following empirical dependencies [7]:

$$M(V, \omega, h_1, h_2) = V[a_1 + a_2(V - \tilde{V})\omega]f_u(h), \quad (4)$$

$$M_c(\omega) = -b\omega, \quad (5)$$

$$f_u(h_1, h_2) = f_{u1}(h_1)f_{u2}(h_2), \quad (6)$$

$$f_{u1}(h_1) = \begin{cases} a_3h^{-1} + a_4, \ \text{for}\, h \in [h_{1\inf},\ h_{1\sup}]; \\ h_{1\inf}, \ \text{for}\, h < h_{1\inf}; \\ h_{1\sup}, \ \text{for}\, h > h_{1\sup}. \end{cases} \quad (7)$$

Additional aerodynamic analysis showed that the function of the influence of the second VGE on the rotor torque can be approximately approximated exponentially:

$$f_{u2}(h_2) = [\exp(1 - h_2/h_{2kr}) - 1]/(\exp(1) - 1), \text{ for } h_2 \leqslant h_{2kr}. \quad (8)$$

Here a_1, a_2, a_3, a_4, b, $\tilde{V}$ — constant coefficients $h_{1\inf}$, $h_{1\sup}$ — lower and upper boundary limit values of the control quantity h_1, determined by WP design features, h_{2kr} — upper limit value of h_2. The cases of the control variables values exit h_1, h_2 from the admissible ranges and the corresponding cutoffs considered in (6) and (7) are necessary only for the correct programming of the corresponding computational problem in finite differences.

For numerical aerodynamic calculations, the Ansys Fluent software package was used; in this case, methods for analyzing unsteady flows in rotating domains based on the approximation of moving grids implemented in this software product were used. For the correctness of the results obtained, two turbulence models were used: k—ε- and RNG k—ε, the use of which in each particular calculation depended on the Reynolds number.

The indicated methods are widely used in studies devoted to the aerodynamics of modern vertically axial WP [15, 16, 19—22]. In particular, in [19], the authors analyzed the twist effect of Dorier type WP turbine blades, and in [21], the possibilities of increasing the aerodynamic quality of the same type blade by using hollows of a special shape on its profile were considered. Article [22] is devoted to the study and modeling of the process of starting a vertically axial WP.

Note that, based on equation of state (3), the above static dependence $\omega_0 = f_0(V_0)$ can be found, if equation (3) is solved sequentially for a number of values of the speed of the unperturbed flow V_0 and, in the limit, the corresponding steady-state values ω_0 are obtained. Fig. 3, *a* shows the time dependences of the rotor angular speedes for wind

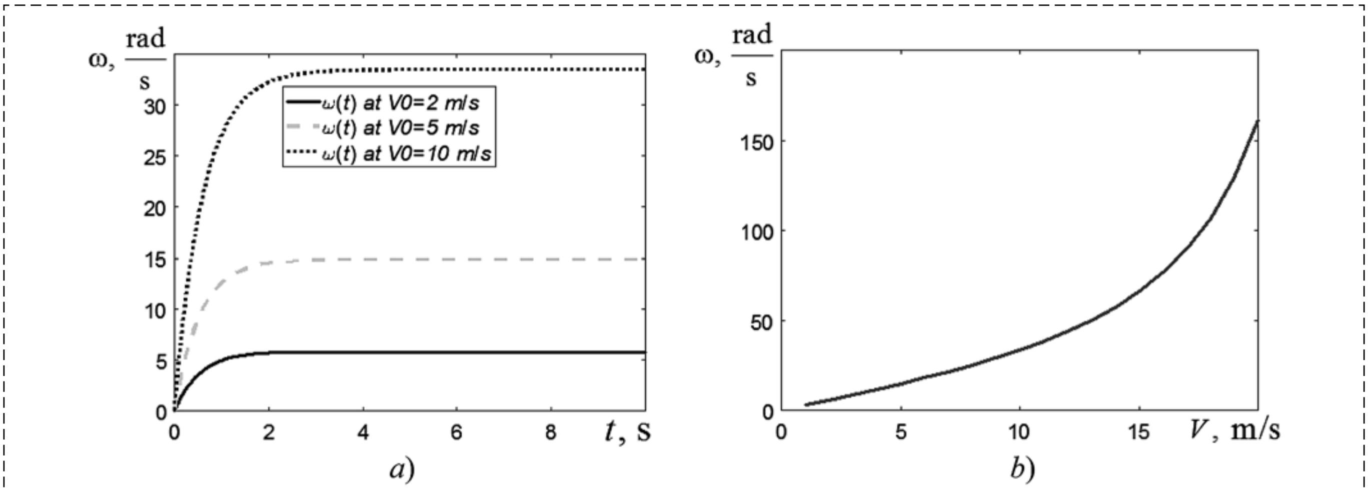

Fig. 3. To the definition of static dependence $\omega_0 = f_0(V_0)$

speedes V_0 = 2, 5, 10 m/s, tending to the indicated steady-state values; figure 3 b shows the corresponding dependence $\omega_0 = f_0(V_0)$.

The actuators of two VGEs will be approximated by first-order aperiodic links [23], i.e. using equations:

$$q_{1,2}\frac{dh_{1,2}(t)}{dt} + r_{1,2}h(t) = f^*_{1,2}(t), \qquad (9)$$

where $q_{1,2}$ and $r_{1,2}$ — constant coefficients, $f^*_{1,2}(t) = q_{1,2}\dot{h}^*_{1,2}(t) + r_{1,2}h^*_{1,2}(t)$ and here the first lower indices correspond to the actuator of the first VGE, and the second to the second VGE. The solution of equations (9) in the general case has the form [24]:

$$h_{1,2}(t) = (1/q_{1,2})e^{-(r_{1,2}/q_{1,2})t} \times \left[\int_0^t e^{(r_{1,2}/q_{1,2})t} f^*_{1,2}(t)dt + q_{1,2}h_{1,2;0}\right] = h^*_{1,2}(t) + [h_{1,2;0} - h^*_{1,2}(0)]\exp[-(r_{1,2}/q_{1,2})t], \qquad (10)$$

where $h^*_{1,2}(t)$ are corresponding dependencies for two VGE without taking into account the response time of the specified actuators; $h_{1,2;0} = h_{1,2}(0)$ — set initial values of control actions $h_{1,2}$.

In the synthesis of the desired controller, we will proceed from the following error equation [23]:

$$\frac{d^2\varepsilon}{dt^2} + A\frac{d\varepsilon}{dt} + B\varepsilon = 0, \qquad (11)$$

where $\varepsilon = \omega_g - \omega$ — regulation error; ω_g — angular speed target value ω; A, B — some constant coefficients that determine the nature of the transition process in terms of angular frequency, in particular, the decay time of this process and the degree of its overshoot.

A feature of the synthesized control system is the presence of two control channels with one state variable to be regulated. In addition, these channels are distinguished as follows. The use of the lower guiding structure for regulation, as shown by aerodynamic analysis [3, 7], does not introduce significant turbulent fluctuations in the flow in the rotor vicinity, however, the use of the aerodynamic brake introduces significant turbulence, which can reduce the quality of control due to the impossibility of accurately accounting for them. Therefore, the ABF use is justified only in high deviation modes $V(t) - V_{0g}$, when the dynamic range of torque changes on the rotor shaft due to the displacement from the normal position of the first VGE, the lower guide structure, is not enough to solve the problem. Therefore, the simultaneous use of two VGEs at once on the same regulation cycle is impractical. Based on (2), we introduce the following rule of switching between modes of using two VGEs:

$$\text{if } |V(t) - V_{0g}| \leq \delta_{V1\max}V_{0g},$$

then only VGE 1 is used;

$$\text{if } V(t) - V_{0g} > \delta V_{1\max}V_{0g},$$

then only VGE 2 is used;

$$\text{if } V(t) - V_{0g} < -\delta V_{1\max}V_{0g},$$

then aerodynamic regulation is not possible with the help of VGE data and ω stabilization is carried out only by electric means.

In this case, based on the equation of state (3) and the error equation (11), the following expressions can be obtained:

$$\frac{1}{J}(M'_V\dot{V} + (M'_\omega + M'_{c,\omega})\dot{\omega} + M'_{h_{1,2}}\dot{h}_{1,2}) + \frac{A}{J}(M + M_c) + B\omega = f(t), \qquad (12)$$

where $f(t) = \ddot{\omega}_g + A\dot{\omega}_g + B\omega_g$, M'_V, M'_ω — corresponding partial derivatives of the moment $M(V, \omega, h_1, h_2)$ by V, ω; $M'_{c,\omega} = dM_c/d\omega$; $M'_{h_{1,2}}$ — partial derivatives with respect to the first and second control variables:

$$M'_{h_1} = -Va_3[a_1 + a_2(V - \tilde{V})\omega]h_1^{-2}f_{u2}(h_2), \qquad (13)$$

$$M'_{h_2} = -(V/h_{2kr})[a_1 + a_2(V - \tilde{V})\omega] \times f_{u1}(h_1)\exp(-h_2/h_{2kr}). \qquad (14)$$

If we express the $\dot{h}_{1,2}$ derivatives from (12) and add equation (3), then the desired system of equations with respect to the state variable ω and two control variables h_1, h_2 takes the form:

$$\begin{cases} \dfrac{d\omega}{dt} = [M(V, \omega, h_1, h_2) + M_c(\omega)]/J; \\ \dfrac{dh_1^*}{dt} = \begin{cases} \dfrac{1}{M'_{h_1}}\{BJ\varepsilon - F(V, \dot{V}, \omega, h_1^*, h_2^*)\}, \\ \text{if } G \equiv |V(t) - V_{0g}| \leq \delta_{V1\max}V_{0g}, \\ 0, \text{ othewise}; \end{cases} \\ \dfrac{dh_2^*}{dt} = \begin{cases} 0, \ if \ G, \\ \dfrac{1}{M'_{h_2}}\{BJ\varepsilon - F(V, \dot{V}, \omega, h_1^*, h_2^*)\}, \\ \text{othewise}. \end{cases} \end{cases} \qquad (15)$$

Here h_1^*, h_2^* characterize the values of control quantities without taking into account the inertia of their actuators; and function $F(V, \dot{V}, \omega, h^*)$ defined by the expression:

$$F(V,\dot{V},\omega,h_1^*,h_1^*) = \\ = [a_1 + a_2\omega(2V - \tilde{V})]f_u(h_1^*,h_1^*)\dot{V} + \\ +\frac{1}{J}[a_2V(V - \tilde{V})f_u(h_1^*,h_1^*) + AJ - b](M + M_c). \quad (16)$$

If we take into account the inertia of VGE triggering according to (10), then we obtain the following estimates for the desired control quantities:

$$h_{1,2}(t) = \begin{cases} \tilde{h}_{1,2}(t), \text{ if } \tilde{h}_{1,2}(t) \in [h_{1,2;\inf}; h_{1,2;\sup}], \\ h_{1,2;\inf}, \text{ if } \tilde{h}_{1,2}(t) < h_{1,2;\inf}; \\ h_{1,2;\sup}, \text{othewise}. \end{cases} \quad (17)$$

where $h_{2;\inf} = 0; h_{2;\sup} = h_{2;kr}$, values $\tilde{h}_{1,2}(t)$ defined by the expressions:

$$\tilde{h}_{1,2}(t) \equiv h_{1,2}^*(t) + [h_{1,2;0} - h_{1,2}^*(0)]\exp[-r_{1,2}t/q_{1,2}]. \quad (18)$$

To compensate the inaccuracy of moment determining on the rotor shaft at various ABF positions relative to the stator bell, we introduce the corresponding observer of the rotor torque perturbation into the developed control system. Let us describe the synthesis process of a reduced observer according to a well-known technique [23, 25, 26].

The adjusted equation of WP rotor state taking into account the unaccounted disturbances on the moment is

$$J\frac{d\omega}{dt} = M(V,\omega,h_1,h_2) + \\ + M_c(\omega) + \Delta M(\delta M, \Delta\omega, \Delta V, \Delta A), \quad (19)$$

where δM — the structural representation error of the moment dependence on the right-hand side of (3) on all variables and parameters (the error of the form of the function M); $\Delta\omega$, ΔV — scalar errors in estimating the angular speed and the module of the flow speed vector at the entrance to WP sensors; ΔA — vector value of the error of estimation of all parameters included in the above dependencies (3)—(9).

Let's introduce the error of perturbation estimation ΔM:

$$\varepsilon_M = \Delta M - \Delta\tilde{M}, \quad (20)$$

where the disturbance assessment $\Delta\tilde{M}$ of ΔM imagine in the form:

$$\Delta\tilde{M} = S(\omega) + z. \quad (21)$$

Here $S(\omega)$ — not yet defined smooth function of a variable ω, and z — the desired function of time, which will go into the general system of equations and will determine the properties and work of the synthesized observer.

Require that the estimation error ε_M satisfy a first-order differential equation:

$$\dot{\varepsilon}_M + a_M\varepsilon_M = 0, \quad (22)$$

where a_M — positive constant characterizing the speed of the observer.

We will first consider a constant perturbation ΔM. It is easy to see that if you impose a restriction on a function $S(\omega)$:

$$dS(\omega)/d\omega = a_M J, \quad (23)$$

then from equations (20)—(23) immediately follows the equation of the observer in the approximation of constant perturbation ΔM:

$$\dot{z} = -a_M[M(V,\omega,h_1,h_2) + M_c(\omega) + a_M J\omega + z]. \quad (24)$$

According to the equations (21) и (23), disturbance assessment $\Delta\tilde{M}$ can be represented as:

$$\Delta\tilde{M}(\omega, z) = a_M J\omega + z. \quad (25)$$

Then the regulator, including the torque perturbation observer constructed here, is characterized by the following system of equations:

$$\begin{cases} \dot{\omega} = [M(V,\omega,h_1,h_2) + M_c(\omega) + \Delta M]/J; \\ \dot{h}_1^* = \begin{cases} \frac{1}{M'_{h_1}}\{BJ\varepsilon - \tilde{F}(V,\dot{V},\omega,h_1^*,h_2^*)\}, \\ \text{if } G \equiv |V(t) - V_{0g}| \leqslant \delta_{V1\max}V_{0g}, \\ 0, \text{othewise}; \end{cases} \\ \dot{h}_2^* = \begin{cases} 0, \text{ if } G, \\ \frac{1}{M'_{h_2}}\{BJ\varepsilon - \tilde{F}(V,\dot{V},\omega,h_1^*,h_2^*)\}, \\ \textit{othewise}, \end{cases} \\ \dot{z} = -a_M[M(V,\omega,h_1,h_2) + \\ + M_c(\omega) + a_M J\omega + z], \end{cases} \quad (26)$$

where

$$\tilde{F}(V,\dot{V},\omega,h_1^*,h_2^*) = F(V,\dot{V},\omega,h_1^*,h_2^*) + \\ +\frac{1}{J}[a_2V(V - \tilde{V})f_u(h_1^*,h_1^*) + AJ - b]\Delta\tilde{M}. \quad (27)$$

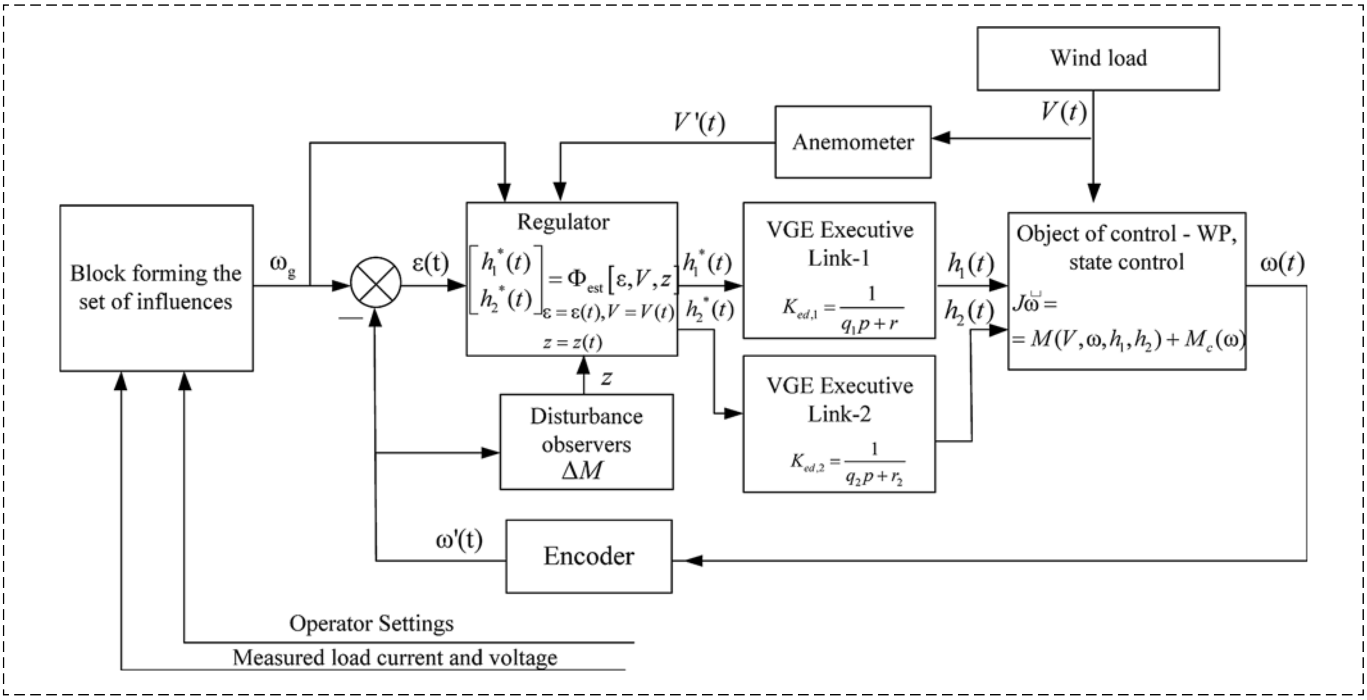

Fig. 4. The functional diagram of the stabilization system of the rotor angular speed

The last three equations of the system (26) indicate that the law of the control variables change $h^*_{1,2}$ includes an estimate of the moment from (25).

Then the resulting control system using two VGEs will include equation (19), the observer equation (24) and the last two equations in (15).

The functional diagram of the stabilization system of the rotor angular speed is shown in Fig. 4.

The master device generates the target law of the rotation angular speed $\omega_g(t)$ changing taking into account the current and voltage at the load and the target setting values of the operator about the required nature of the power supply of this load. Further, on the basis of ω_g and output ω' of the rotor angular speed ω meter (encoder), an error signal is generated $\varepsilon = \omega_g - \omega' \approx \omega_g - \omega$, which arrives at the controller. The latter also receives a signal z from the rotor moment perturbations observer; this observer works according to the last equation in (26). The controller generates control signals $h^*_1(t)$, $h^*_2(t)$ for two WP variable geometry elements under consideration in accordance with the second and third equations of the system (26). These signals are fed to the corresponding actuators, which change the position of two VGEs, thereby fending off changes in wind speed in order to stabilize the angular speed ω.

Modeling the operation of the synthesized controller

Consider the results of modeling the synthesized controller of the rotor rotation angular speed.

Fig. 5, *a* (see the fourth side of covered) shows the time dependence of the angular speed at a constant component of the wind speed V_0 = 5 m/s, target rated rotor frequency $\omega_g = 3\pi$ rad/s and various amplitudes Av of this disturbance: Av = 1 m/s, 2 m/s, 2,5 m/s, 3,35 m/s, for a controller with system of equations (15) without taking into account the observer of perturbations of the torque. Other parameter values:

$$a_1 = 0{,}0716,\ a_2 = 1{,}704 \cdot 10^{-4},$$
$$a_3 = 0{,}202,\ a_4 = 0{,}692,$$
$$b = 0{,}0019, \alpha_V = -0{,}1\ \text{s}^{-1},$$
$$\Omega_V = 2\pi\ \text{rad/s},\ h_{2kr} = 0{,}3\ \text{m};$$

actuator transient convergence parameters ИГ-1,2: $p_{1,2}/q_{1,2} = 5\ \text{c}^{-1}$.

Fig. 6, *a* and 7, *a* (see the fourth side of covered) show the time dependences of control variables $h_1(t)$ for VGE-1 (b) and $h_2(t)$ for VGE -2 (c) corresponding to the above values of the amplitudes Av perturbations.

From the dependences shown in Fig. 5, *a*, 6, *a*, 7, *a* (see the fourth side of covered) it follows that, starting from some characteristic time instants, the first VGE ceases to be involved by the control system, since condition G introduced in (15) ceases to be fulfilled starting from these instants. Obviously, the larger the amplitude of disturbances Av, the later such a moment occurs, since the longer the current wind speed will fall into a given corridor relative to the desired wind speed, which is equal in this case $V_{0g} = f_0^{-1}(\omega_g) = 3,4$ m/s. It can also be seen from this figure that the angular speed enters the permissible corridor for a time of less than 3 with overshoot of less than 50 % for all considered *Av* values, which corresponds to the initial data on the quality of regulation $\Delta\omega_g = 0,05\omega_g$, $\Delta T'_p = 5$ s, $\eta_\omega = 50$ %.

Fig. 5, *b*, 6, *b*, 7, *b* (see the fourth side of covered) shows similar relationships to Fig. 5, *a*, 6, *a*, 7, *a*, only for a controller with system of equations (26), which includes an observer in the constant perturbation approximation, in this simulation with the value ΔM = const = 1 Nm; observer speed set equal $a_н = 3$ s.

A comparison of the graphs shown in Fig. 5, *a*, 6, *a*, 7, *a* with the corresponding graphs presented in Fig. 5, *b*, 6, *b*, 7, *b* (see the fourth side of covered) shows that the introduction of an additional constant unmeasured disturbance to the right side of the equation of the state $\Delta M = 1$ Nm can be effectively counterbalanced using a reduced observer with preservation of the transition time process and a slight increase in the degree of overshoot — by 4 %.

Thus, the constructed controller is capable of effectively counteracting the influence of wind disturbances in a wide range of the current speed deviations from desired for a given frequency target value, and arbitrary excesses of the current wind speed over the desired speed V_{0g} are permissible, since the aerodynamic brake flap is able to vary the torque on the shaft up to a complete stop rotor. On the other hand, the lower limit of the wind speed acceptable for the considered control system is given by the first condition in (2), which is determined by the dynamic range of regulation according to the first VGE: $-\delta_{V1\max}V_{0g} \leqslant V(t) - V_{0g}$, in this case $\delta V_{1\max} = 0,3$.

Therefore, the proposed speed controller of WP rotor, changing the position of WP construction control elements depending on the measured speed of the wind disturbance, can increase efficiency and reliability of the plant work as well as quality of electric power generated by it.

Such aerodynamic speed control at the current stage of development of precision mechanics, actuators of WP components actuators and manufacturing technology of precision parts can work in conjunction with conventional methods of electrical stabilization of the generator frequency. Such joint work significantly reduces the quality requirements of the corresponding electrical equipment by reducing the dynamic range of the generator frequency control by preliminary aerodynamic speed control of the wind-driven power plant rotor speed.

Conclusion

In the paper, a regulator that stabilizes the rotor rotational speed of a vortex type wind-driven power plant using two variable elements of its geometry was synthesized. Based on the reduced observers, an additional loop for estimating rotor torque disturbances in the approximation of the constancy of these disturbances was introduced.

This regulator is able to maintain the value of the rotor angular speed in a sufficiently small permissible corridor (not more than 5 %) with wind disturbances limited from above only by structural strength requirements imposed on the installation elements. This is achieved by introducing an additional control element — the aerodynamic brake flap.

The application of the proposed method for WP rotor speed controlling will significantly increase the control system adaptability of its output characteristics; significantly expand the dynamic range of torque control on the wind-driven power plant rotor, as well as increase the robustness of these characteristics to external wind and internal structural parametric disturbances.

The use of vertically axial vortex type WP with the rotor speed aerodynamic control discussed in this article as part of complex power plants can significantly increase the efficiency of the latter.

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