

# Control law synthesis of the wind-driven power-plant with variable geometry

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## Abstract

The analysis and synthesis of aerodynamic properties of the wind-driven power-plant (WP) construction with a vertical axis of rotation and useful interference of the stator and the rotor, that exceeds classical type analogues on energy characteristics, were conducted. The required functional dependence of the rotor rotative moment of WP on the angular speed of its rotation and the wind speed on the basis of aerodynamic optimization and researches of optimal shape and construction of WP was obtained. Respective aerodynamic power was calculated. The example of frequency stabilization of the rotor rotation through control of variable element of optimized form WP construction was considered. Method of maintaining the given angular speed of the rotor with a given deviation for a given time was proposed.

**Keywords:** aerodynamic optimization, wind-driven power-plant, synthesis, energy characteristic, interference.

Received on 22 October 2018, accepted on 16 February 2019, published on 21 March 2019

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doi: 10.4108/eai.13-7-2018.157036

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## 1. Introduction

The problem of increasing efficiency of existing wind-driven power-plants (WP) is considered in several articles [1-8]. A further task is to develop methods for designing WP constructions, the basic idea of which creation should be a sharp increase of efficiency of operation system of aerodynamically and electromechanical connected WPs compared to the corresponding set of unconnected WPs.

## 2. Possible development direction of perspective type WP

The advantages of WP with vertical axis of rotation [4-7,13], with respect to the classic, with the propeller type rotor is that they are independent from the wind direction, the lower speed of the rotor start-up and the ability to manufacture WP that are more rapidly under other equal conditions. The construction "rotor in the ring" greatly

reduces the losses caused by the flow separation on the blade tips [7, 14, 15]. Furthermore, using together with a ring also the output device (the bell) leads to a significant decrease of rotor minimum speed run of (to 45% of the wind speed). In [4], as well as in [6-7] WP using useful interference of the stator and rotor are studied. Vortical type WP [8] with a vertical axis of rotation is capable to reduce the power of hypersonic noise generation, arising from rotational moments on the side of the rotor axis. In the patent application [9] the vortex-type WP, which, in contrast to WP patent [8] has an additional guiding structure which contributes to a significant increase in rotor rotational moment, and a decrease in uneven distribution of pressure at the bottom rotor part is considered. Available WP allow only change the orientation of rotational rotor axis of WP to track wind speed vector. More appropriate is to manage due to the special variable geometry elements (VGE).

### 2.1. Aerodynamic optimization of WP construction

WP development, using useful interference of stator and rotor, and VGE, requires solving the problem of analysis and synthesis of aerodynamic properties of WP construction, which comes down to an aerodynamic optimization of WP form and requires to use CFD-analysis (computational fluid dynamic). For WP without VGE, as a criterion for optimizing the geometry, is advisable to choose maximum average  $\langle P \rangle$  on the range  $Q$  of all possible sets  $\{V, \omega\} \in Q$  of values of useful power on the rotor:

$$P_Q|_{U_{geo, opt}} = \max_{\{U_{geo}\}} [P_Q|_{U_{geo}}] \quad (1)$$

where the maximum search is performed on a given set  $B$  of possible forms  $U_{geo} \in B$  of the rotor, the bell and their relative positions  $U_{geo, opt}$ , - optimal in this sense WP geometry.

If WP contains both constructively immutable ( $U_{geo}^{stat}$ ), and a varied geometry ( $U_{geo}^{stat}$ ), than in the first approximation, to simplify arising in such formulation problem of WP form optimization, the "static" of its component may be first optimized and  $U_{(geo, opt)}^{stat}$  obtained, and then, based on the latest, solve the problem of VGE search  $U_{geo, opt}^{var}$ , which deviation from its neutral position would ensure the specified objective qualities of WP as a whole.

As a result of aerodynamic optimization and subsequent full investigation of obtained optimum form and WP construction, the required functional dependence  $M = M(V, \omega)$  of WP rotational moment on two arguments: the angular speed  $\omega$  of the rotor and the wind speed vector  $V$  were obtained

## 3. Aerodynamic optimization

### 3.1 Example of aerodynamic optimization.

Perform aerodynamic WP optimization, discussed in the patent [11]. Given: geometry of WP rotor, the initial version of the bell geometry and construction of the rotor [10]. Rotor sizes: maximum diameter  $D_{max} = 1.25m$ ; height  $H = 0.32m$ . Bell sizes: minimum (upper) diameter  $D_{rastrmin} = 1,16m$ ; maximum (lower) diameter  $D_{rastrmax} = 2,23m$ ; height  $H = 0,428m$ . The range of wind load:  $V = 3 \dots 30 \text{ m / s}$ , the original range of angular speeds of the rotor rotation  $\omega = 0,5 \dots 20 \text{ rad / s}$ . It is necessary to obtain optimal bell form, for a given rotor form and the corresponding constructing of obtained bell with the rotor, ensuring the implementation of the criterion (1) As a result of the aerodynamic optimization optimal from the point of view of given criterion and given set of basic forms of bell geometry and construction of the rotor are obtained (Fig. 1.) [16].

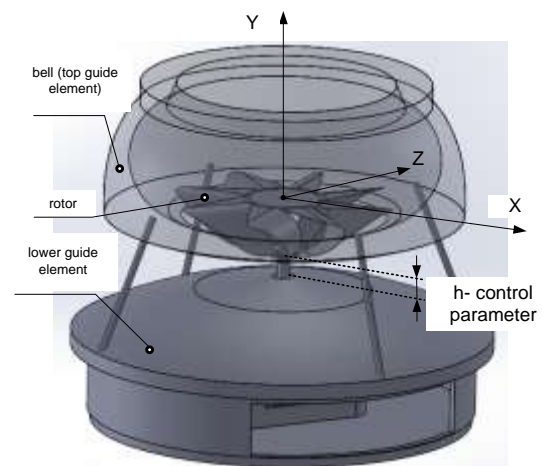


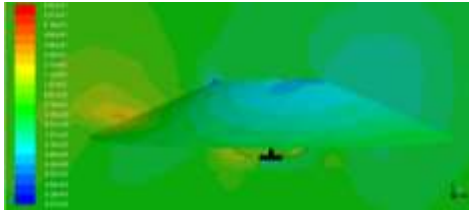
Figure 1. WP construction of optimized bell with rotor.

### 3.2 Cfd-analysis of the optimal form WP.

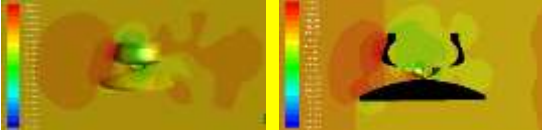
Typical pressure distribution are obtained in the plane OXY at a flow rate of  $V = 10 \text{ m / c}$ , angular rotor speed  $w = 6,28 \text{ rad / s}$  for three cases: rotor without bell (2a), rotor with the initial bell (2b) and optimized (2c) forms (Fig. 2.).



a) for a single rotor



b) for the initial construction «rotor+bell»

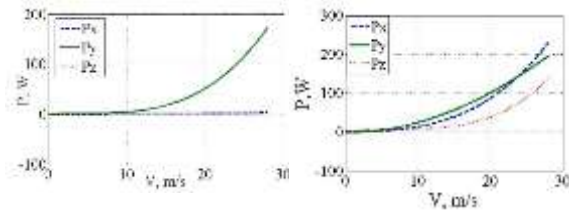


c) for optimized construction «rotor+bell»

**Figure 2.** WP construction of optimized bell with rotor.

### 3.3. Calculation of wind power.

Fig. 3 shows diagrams of dependence of rotor rotation useful power to the OY axis (Fig. 1) and corresponding destabilizing rotation relative to OX and OZ axes for the cases of the original (left) and optimized (right) WP forms at  $\omega = 6,28 \text{ rad / s}$



**Figure 3.** Diagrams of dependence useful  $P_y$  and adverse  $P_x$ ,  $P_z$  of aerodynamic power from the incoming flow rate  $V$ .

These graphs shows that by using optimized geometry (see. Fig. 1) in the wind speed range from 5 to 20 m / s useful aerodynamic power on WP rotor increases more than twice compared with the original WP geometry.

Let us compare the energy efficiency of obtained optimized WP form with wind-driven power-plant of the Dnepropetrovsk CB "South", which has the power 500 kW at a wind speed 12.9 m / s, with the diameter of the screw  $D_2 = 38,3 \text{ m}$  [6]. To do this, define how much power would obtained optimized form WP have with the same size and speed of the wind flow, which for the considered analogue.

WP useful power can be calculated using the formula [17-21]:

$$P_1 = M(V, \omega) \cdot \omega \cdot \langle \eta_{red} \rangle \cdot \langle \eta_{gen} \rangle \quad (2)$$

where  $\langle \eta_{red} \rangle$ ,  $\langle \eta_{gen} \rangle$  - the average values of of the gearbox and the generator efficiency, the values of which belongs to, as a rule, following ranges  $\eta_{red} = 0.9 \div 0.95$ ,  $\eta_{gen} = 0.7 \div 0.9$ : [5].

If our installation has a diameter  $D_2$ , than the rotational moment, generated by it at speed  $V_{w2} = 12,9 \text{ m/s}$  and sufficiently small angular speed of the rotor  $\omega = 6,28 \text{ rad / s}$ .

$$P_2 = P_1 (D_2 / D_1)^3 (V_{w2} / V_{w1})^2 = 1034 \text{ kW} \quad (3)$$

where with sufficient accuracy for practice suggested that the dimensionless coefficient of the rotational moment does not change at this scale.

Thus, if the rotor used in our apparatus, having diameter  $D_2$ , than the corresponding optimized WP would have a power output more than twice exceed the power of WP-500 of Dnepropetrovsk "Southern".

This result shows that using optimized bell forms for special rotor forms with a vertical axis of rotation and is perspective and not inferior in increasing of efficiency wind using by other methods discussed, for example, in [1-8].

### 4. Adjusting mechanical parameters of WP

During considering WP control the following tasks are raised: a) access to necessary angular speed of the rotor rotation for a minimum time; b) maintaining a predetermined angular speed of the rotor with a predetermined deviation for a predetermined time; c) maximization of wind energy generated by the rotor.

As an example, for an optimized WP form obtained in p. 3 (Fig. 1), let's consider the solution of the problem of maintaining a given angular speed of the rotor within a predetermined range under wind speed perturbation. First of all, write the equation of rotational motion of WP:

$$J \frac{d\omega}{dt} = M(h, V, \omega) + M_r(\omega), \quad (4)$$

where  $M(h, V, \omega)$  - the dependence of the rotating axis aerodynamic moment of the rotor on the angular speed of its rotation  $\omega$ , the wind speed  $V$  and the control parameter VGE  $M_r(\omega)$ ; - moment of resistance to the rotor rotation that occurs at the contact it with the stator;  $J$  - reduced moment of the rotor inertia relative to the axis of rotation.

We assume that WP has one controlled geometry element - the lower guide structure characterized by variable geometry parameter - the distance from the top of the structure to the bottom of the rotor (Figure 1).

As external disturbances we will consider wind speed module  $V$  at its fixed direction as time function  $V^*(t)$  of aperiodic transition of speed perturbation:

$$V(t) = V^*(t) = V_0 + A_v \exp(\alpha_v t) \sin(\Omega_v t) \quad (5)$$

where  $V_0, A_v, \alpha_v, \Omega_v$  some constant values. Let the control system is equipped with special sensors that allow certain frequencies to obtain values  $V(t)$ .

The inertia of the actuator VEG triggering, regulating the value  $h$ , leads to the presence of a transient process (TP), which occurs when establishing the objective function  $h^*(t)$ . The latter is produced by the regulator, which we consider below. The specified TP with sufficient accuracy can be described by a differential equation of the first order:

$$q\dot{h}(t) + rh(t) = f^*(t) \quad (6)$$

where  $q$  and  $r$  - some constant coefficients, and the ratio  $r/q$  has the meaning of the decay time constant of the transition process,  $f^*(t) = q\dot{h}^*(t) + rh^*(t)$ .

It is necessary to find a control law  $h(t)$  that provides deviation of angular speed  $\omega$  from the set nominal value  $\omega(0)$  not greater than a predetermined limit  $\Delta\omega_{max}$ .

Numerical investigation of this optimized WP form led to the following approximating according to aerodynamic moment on the shaft:

$$M(h, V, \omega) = V[a_1 + a_2(V - V_0)\omega]f_u(h) \quad (7)$$

where the function  $f_u(h)$  is defined by the expression

$$f_u(h) = \begin{cases} h_1, & \text{npu } h < h_1; \\ \frac{a_3}{h} + a_4, & \text{npu } h \in [h_1; h_2]; \\ h_2, & \text{npu } h > h_2, \end{cases} \quad (8)$$

and the constant coefficients in (7), (8) are

$$a_1 = 0,684 H \cdot s, a_2 = 1,550 \cdot 10^{-3} H \frac{s^3}{m}, a_3 = 0,0921 m,$$

$$a_4 = 0,858, V_0 = 3 m/s, h_1 = 0,02 m, h_2 = 0,65 m.$$

Reproduced inertia moment assume to be equal to  $J = 100 kg \cdot m^2$  and resistance moment on the rotor shaft will be given by approximating dependence obtained based on studies WP vortex type described in [10]:

$$M_r = -b \cdot \omega \quad (9)$$

where  $b = 0,0019 H \cdot m \cdot s$ .

Dynamic control range at the time (7) of rotation, ie, ratio of the maximum value of the time to a minimum by varying  $h$  is  $k_u = 2,7$ . The minimum value of control range  $h_1$  is due to technological limitations, and the maximum  $h_2$  - leveling the aerodynamic effect of the lower guide structure WP rotor at a sufficient distance from its last.

Let tolerance for frequency deviation  $\omega$  from the nominal value  $\omega = 6,28 rad/s$  is  $\Delta\omega_{max} = 0,3 rad/s$  and external wind disturbance, defined by equation (5), characterized by the values of coefficients

$$V_0 = 5 m/s, A_v = 1 m/s, \alpha_v = -0,5 s^{-1}, \Omega_v = \pi rad/s.$$

The regulation error  $\varepsilon = \omega_0 - \omega$  will be represented as a first order equation [11]:

$$T\dot{\varepsilon} + \varepsilon = 0, \quad (10)$$

where  $T$  - the angular frequency transient time constant.

The regulation law will be obtained if we express  $\dot{\varepsilon}$  from (10) and substitute into the equation of the rotor motion (4), and then express the controlled variable  $h^*$ :

$$h^*[\varepsilon, V] = \frac{a_3 V [a_1 + a_2(V - V_0)(\omega_0 - \varepsilon)]}{b(\omega_0 - \varepsilon) + \varepsilon J T^{-1} - a_4 V [a_1 + a_2(V - V_0)(\omega_0 - \varepsilon)]} \quad (11)$$

To obtain the real impact of VGE on the control object - the rotor, it is necessary to solve equation (6). This solution can be written in quadratures and then transformed after integration in parts to the following form [12]:

$$h(t) = (1/q)e^{-(r/q)t} \left[ \int_0^t e^{(r/q)t} f^*(t) dt + qh_0 \right] = h^*(t) + [h_0 - h^*(0)] \exp[-(r/q)t], \quad (12)$$

where  $h_0 = h(0)$  - preset initial value  $h$  and taken into account that  $f^*(t)$  associated with  $h^*(t)$  by ratio  $f^*(t) = q\dot{h}^*(t) + rh^*(t)$  according to (6).

The block diagram of the control parameter  $h$  for mechanical stabilization of the angular speed of rotation of the rotor is shown in Figure 4.

The driver forms the law of the angular speed of rotation variation  $\omega_0$  under the influence of the measured current and voltage on the load and the target settings of the operator on the nature of the power supply of this load. Further, based on  $\omega_0$  and output  $\omega'$  of the angular speed meter  $\omega$  rotor (encoder), an error signal is generated  $\varepsilon = \omega_0 - \omega' \approx \omega_0 - \omega$ , coming to the regulator. The latter, under the influence  $\varepsilon$  and assessment  $V' \approx V$  of a wind speed meter  $V$  (anemometer), performs conversion  $\Phi_{est}[\varepsilon, V]$  considering the given objective function  $\omega_0$ . Output value  $h^*(t)$  of regulator then fed to the block of the actuator VEG with a transfer coefficient  $K_{ed}(p) = 1/(qp + r)$ . Output of this block  $h(t)$ , taking into account the inertia of the actuator actuation together with the current wind load  $V$ , then directly affects on WP, which is reflected in the right side of the rotor state equation. The feedback of the control system is closes the next value of the rotor angular speed, arriving at the encoder, and then - at the adder.

Note that in the regulator empirical dependencies are used  $M_r(\omega)$ ,  $M(h, V, \omega)$  according to (7) and (9).

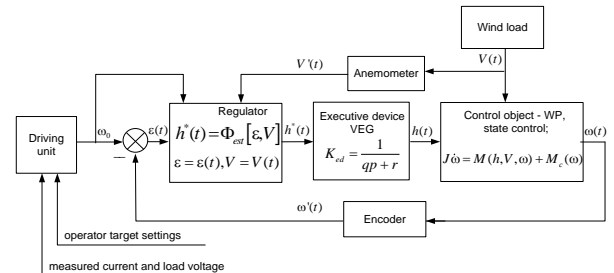
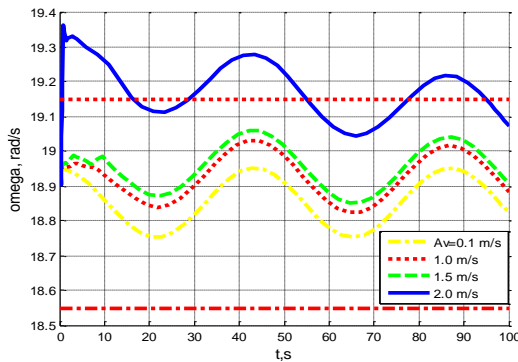
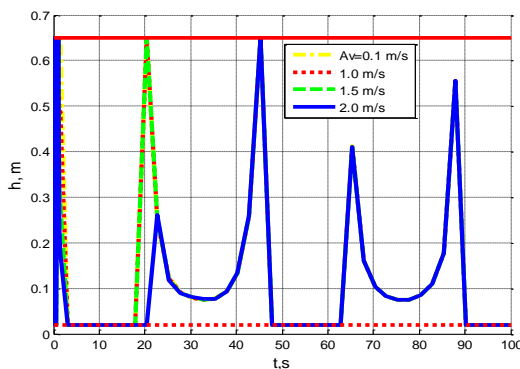


Figure 4 - Structural control scheme of the  $h$ - parameter for the mechanical stabilization of the angular speed of rotor rotation

Figures 5 and 6 show diagrams of dependence and their respective departments from time with the initial conditions  $h(0) = 0,5(h_1 + h_2)$ ,  $m$ ,  $\omega(0) = 6\pi + 0,1$ ,  $rad/s$  for several values of the amplitudes of the oscillations of the wind  $A_v$ : dashed curve – for  $A_v = 0,1 m/s$ ; point -  $1 m/s$ ; dashed -  $1.5 m/s$ ; solid -  $2 m/s$ . It was set  $T = 0.1 s$ .



**Figure 5.** Diagrams of dependence  $\omega(t)$  for several values of the amplitudes of the wind oscillations  $A_v$ .



**Figure 6.** Diagrams of dependence  $h(t)$  for several values of the amplitudes of the wind oscillations  $A_v$ .

The graphs given in Fig. 5, shows that for a given dynamic range control  $k_u = 2,7$  stabilization of rotor speed with a given accuracy  $\Delta\omega_{max} = 0,3 rad/s$  possible with the amplitude of oscillation of the wind speed of at least satisfying  $A_v \leq 1,5 m/s$ . At the maximum speed  $A_v = 0,2 m/s$  corresponding to the function  $\omega(t)$  exceeds the permissible range  $\Delta\omega_{max}$  by 50%. The graphs given in Figure 6, shows that during the first 30 seconds of the deviation curves  $h(t)$  for different  $A_v$  from each other are not visible, because according to (5) of wind fluctuations from time present an exponential factor  $\exp(-0,5 t)$ . The functions  $h(t)$  are not smooth around the time range as a result of their forced cut-off when the limit values  $h = h_1, h_2$  according to (8). To increase the range of oscillation amplitudes  $A_v h$  of wind perturbations, where possible to stabilize the rotational speed, it is necessary to increase the dynamic range regulation  $k_u$  by  $h$ , or to

increase the maximum allowable deviation  $\Delta\omega_{max}$ . The introduction of additional elements of variable geometry can improve the dynamic range of rotative moment control.

The considered control of the mechanical speed of rotor rotation allows, firstly, to regulate the power at the load, limiting it at the right moment; secondly, to stabilize the electrical frequency at the generator output, thereby reducing the ripple coefficient at the rectifier output. The latter possibility is certainly important for the battery and inverter correct operation of WP electrical system. As a result, WP efficiency is increased; the allowable dynamic range of wind loads and the quality of generated electricity are expanded.

## 5. Conclusion

It is shown that WP construction on the basis of useful interference of stator and rotor is promising. Analysis of WP form with vertical axis of rotation, axisymmetric stator and rotor resulting from aerodynamic optimization [14] showed that the usage of useful interference of rotor and stator, on power characteristics superior to classical WP.

Using variable geometry elements significantly contributes the efficiency and adaptability [11] control system by output WP characteristics, expands the dynamic range of moment control on the WP rotor.

## Acknowledgements

This work was supported by the RFBR grant No. 1-KV-1-2018-18-08-00473 "Development and research of methods for optimizing and managing energy conversion processes in power plants of a complex type, including those that convert a continuous medium flow.

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