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SUBSTANTIATION OF ADAPTIVE SELF-ADJUSTING SYSTEM OF AUTONOMOUS WIND ENERGY TURBINE

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Abstract—*The design principles of adaptive control system of gearless electric wind turbine in the maximum wind turbine power factor for variable speed wind is considered.*

Index Terms—Gearless electric wind generator; adaptive power control system load.

I. INTRODUCTION

Energy efficiency dispersed generation of electricity from wind flows is fundamentally possible under technical use of low winds that are characteristic for more than 80 % of Ukraine territory, where the average annual wind speed does not exceed 4.5 m/s. But traditional methods of electromechanical systems constructing arent's suitable for the solution of this problem. Using traditional systems of frequency control speed wind turbine (WT) by axial turning blades does not permit to operate in a continuous maximum power factor mode. The current level of power electronics development allows constructing the wind turbine electrical systems with flexible transmission of electricity to the grid or autonomous power load. However it is necessary to take into account not only the technical capabilities of adaptive control, but the gearless electricity generator limits of regulation in the maximum power factor WT mode that it determines the relevance of research.

II. PROBLEM STATEMENT

The technical idea of adaptive control systems construction and regulation of autonomous wind turbines (AVEU) is known for a long time. It is described, for example, the features of adaptive system in the maximum wind turbine power factor mode with taking into account the inertial parameters [1]. However, electric generator model of the traditional type is considered without estimation of its power capacity regulation possibilities. Maximum use of installed capacity AVEU is achieved, for example, for the adaptive control process of simultaneous electricity and heat production [2]. The general objective of adaptive regulation system of AVEU [3] is mode maintenance of maximal coefficient of variable wind flow energy power utilization by the known graphics functions depending on rapidity. Similar principles of adaptive control are proposed in [4] with some different structural configuration of the algorithms system. However, for adaptive AVEU as shown in [5], it is necessary to analyze the character of informative parameters of the incoming energy flow taking into account the rotating mass inertial parameters of WT. Besides the structure synthesis principles of self formed algorithms system developed in [2] is very generally without substantiated methods of energy efficient electricity load control. Consideration the influence of stochastic character wind speed for aeromechanical system inertial parameters is shown in [6], but the principles of power generation control with cubic dependence on wind speed aren't considered.

III. THE PURPOSE OF RESEARCH

The purpose of research is the substantiation of electrotechnical complex of aero-electromechanical system with adaptive load control in the mode of maximum power factor under continuously variable wind speed.

IV. RESEARCHES RESULTS

The general principle of AVEU adaptive control system synthesis is based on the use of known dependence of power factor from WT rapidity and torque from variable wind speed, as shown, for example, in [3]. The WT rotation frequency is indicated here as an independent input parameter, but this parameter according to [5] should serve as dependent function of wind speed under the influence of aeromechanical system inertia moment. Therefore, the block-diagram of general structure of adaptive control system Simulink-model of wind turbines is represented on Fig. 1.

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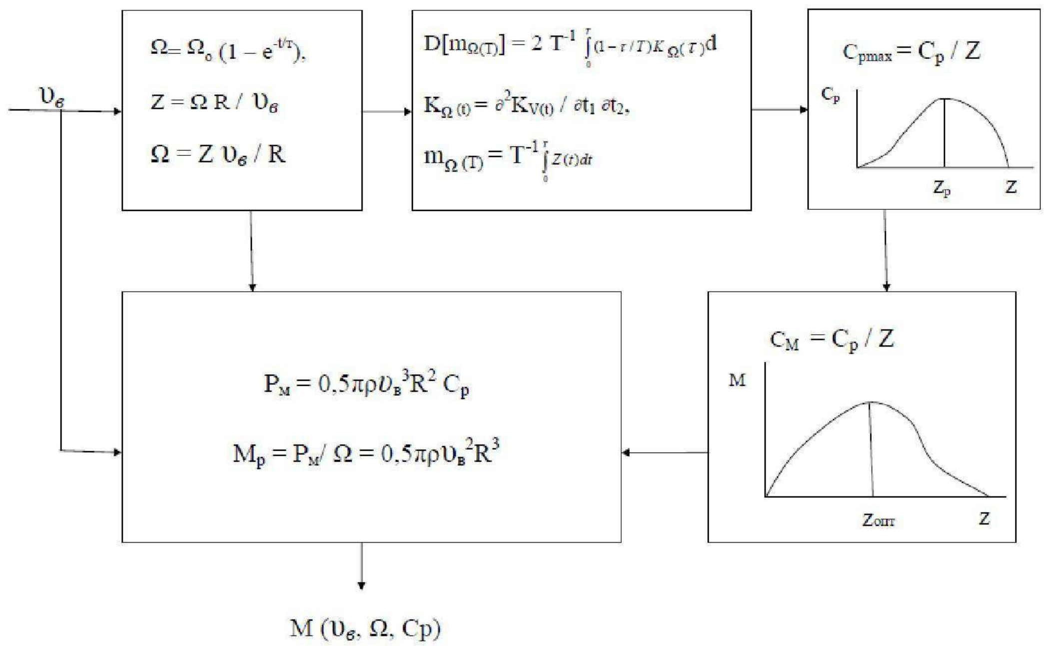

Fig. 1. Block-diagram of general structure of adaptive control system Simulink-model of wind turbines

In functional blocks it is used the functions of output indexes from weight and size and aerodynamic WT parameters with known laws of variance distribution, correlation and mathematical expectation of random values of rotation frequency under variable speed wind ($\upsilon_в$).

The only defining geometrical parameter is the length of the blades, i.e. radius WT (R), and all their other dimensions that affect on aerodynamic quality, are reflected in the value of rapidity Z. The power factor C_p and moment coefficient C_M are dependent on the ratio rotation frequency WT and wind speed. That is why, the power function can be set by the only function of wind speed, which simplifies the investigated functional model that displays behaviors of aeromechanical system that perceives wind energy (eV).

For analyzing regularities of gearless electromechanical system behavior without mechanical units, attached to the WT it is necessary to analyze the block diagram of aerial electromechanical macrosystem (Fig. 2).

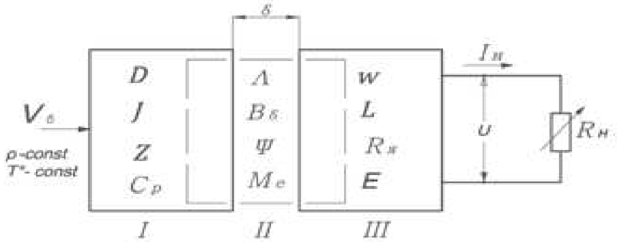

Fig. 2. Block diagram of conservative aero-electromechanical macrosystem

In this scheme the power function is given only by wind speed ($V_в$) under the condition of air environment invariability and mutually subordinates aeromechanical (I), magnetic (II) and electric (III) subsystems are given by lumped parameters: D, J, Z, C_p – respectively diameter, the moment of inertia, rapidity and power factor WT; Λ, $B_б$, ψ, M_e – respectively magnetic conductivity, induction, flux and electromagnetic torque; w, L, E, $R_я$, $R_н$, I – respectively the number of turns anchor stator windings, inductance, EMF, winding anchor internal resistance, adjustable resistance and load current.

The feature of the proposed scheme, is the image of the magnetic system with concentrated parameters of interaction between the moving aeromechanical and statically fixed electrical systems, separated by working air gap δ, which adequately reflect the essential features of the physical model of contactless inductor generator. The process of electromechanical conversion of eV is carried out by energy magnetic field periodic change in the air gap by the power interaction of rotor moving ferromagnetic elements, by mechanical movement of which the value of magnetic conductivity is periodically changed and therefore flux linkage. In this scheme it is specified the minimal necessity number of defined parameters of each system. For example, the aeromechanical system is given by the major structural geometric parameter (diameter of WT) and related with structure dynamic parameters – moment of inertia and rapidity, and power factor. The last two parameters quantitatively account the indexes of aerodynamic quality of aeromechanical system.

The mathematical expressions that describe the physical processes in electromechanical system and electrotechnical complexes based on the laws of electrodynamics, the theory of electric and magnetic circuits and motion mechanics of aeromechanical system.

For the simplest and also the most energy-efficient variant of electromechanical systems using permanent magnets to create an excitation magnetic field, the electromagnetic processes of magneto statics are described by Maxwell differential equations system

$$\begin{aligned} &\vec{B} = rot\vec{A},\ \mu_a \vec{H} = rot\vec{A}; \\ &rot\vec{H} = \vec{j},\ div\vec{A} = 0, \end{aligned} \quad (1)$$

where $\vec{B}$ is the magnetic induction; $\vec{H}$ is the magnetic field strength; μ_a is the relative magnetic permeability; $\vec{j}$ is the current density in the armature winding; $\vec{A}$ is the vector magnetic potential with one component by rotor rotation angle φ around the axis, i.e. $\vec{A}(0,0,A_\varphi)$.

Using mathematical operator ∇, the expression (1) will be as follows:

$$\begin{aligned} &\vec{B} = \nabla\times\vec{A},\ \mu_a \vec{H} = \nabla\times\vec{A}; \\ &\nabla\times\vec{H} = \vec{j},\ \nabla\times\vec{A} = 0. \end{aligned} \quad (2)$$

Energy interaction occurs between mechanical and electrical systems without mechanical contact through a magnetic field, which is determined by the vector magnetic potential from a system of equations for magnetic circuit different parts of the electromechanical converter:

$$\begin{cases} \text{in a magnetic circuit of stator and rotor,} \\ \nabla\times[(\mu_\phi\mu_0)^{-1}\cdot\nabla\times\vec{A}] = 0 \\ \text{in permanent magnet material,} \\ \nabla\times[\nabla\times\vec{A} - \vec{B}_r] = 0 \\ \text{in the air gap and diamagnetic motor casing,} \\ \nabla\times\nabla\times\vec{A} = 0 \\ \text{in the stator winding,} \\ \nabla\times\nabla\times\vec{A} = \vec{j} \end{cases} \quad (3)$$

where μ_ϕ is the permeability of magnetic core electrical steel.

Taking into account the state equation a magnetic material $\vec{B} = \mu_\phi\mu_0\vec{H} + \vec{B}_r$, the general equation is represented as

$$\nabla\times[(\mu_\phi\mu_0)^{-1}\nabla\times\vec{A} - (\mu_\phi\mu_0)^{-1}] = j. \quad (4)$$

This universal equation for calculating the electromechanical system magnetic field under known geometrical and technical parameters of the magnetic circuit constituent elements.

The electric and magnetic systems interdependence is described by the second Maxwell equation:

$$\nabla\times\vec{E} = \partial B/\partial t, \quad (5)$$

where $\vec{E}$ is the electric field strength which is proportional to the EMF in the stator anchor winding.

Combining theoretical calculation methods of electromagnetic fields and electrical circuits by Kirchhoff's second law it can be written equilibrium differential equation for the circuit:

$$\partial\psi/\partial t = U + (R_я + R_н)I. \quad (6)$$

The general expression of flux linkage by vector magnetic potential for anchor winding will be

$$\psi = \frac{w}{S}\int_S A\varphi 2\tau l\, ds, \quad (7)$$

where w is the number of winding turns; τ, l is respectively pole division and its axial length; S is the normal surface area of the pole.

Electromagnetic moment of the electromechanical system under a balanced moment of excitation magnetic fluxes is formed by anchor winding current and generally proportional to the gradient of the magnetic field energy changes W_M in the generator air gap that can be written as

$$M_e = grad\ dW_M, \quad (8)$$

where dW_M is magnetic field energy change caused by mechanical movement of the rotor pole elements through air gap.

In given electromechanical system the electromagnetic torque can be determined by several methods, in particular, for inductor-type generator under constant current of anchor winding through the harmonious changing magnetic conductivity and thus linkage flux of electromechanical system, (since $\psi = Iw^2\Lambda$), which will be described as follows:

$$M_e = dW_M/d\varphi = 0{,}5\, I^2w^2 d\Lambda/d\varphi = 0{,}5 I d\psi/d\varphi. \quad (9)$$

For given electromechanical system the mechanical model of arc-stator generator with certain conditions can be represented by quite hard rotating rotor relative to the horizontal axis, the most common recording of mechanical rotary motion law of which is Lagrange differential equation of the second kind:

$$\frac{d}{dt}\frac{dW_K}{d\Omega} - \frac{dW_K}{d\varphi} = M_p - M_e, \qquad (10)$$

For one-dimensional rotary motion, when variable coordinates are polar angle φ of rotor rotation and relative angular velocity Ω without structure elastic deformation, all the kinetic energy W_K of mechanical system accumulates in a total rotating mass and interacts with the electromagnetic torque through ferromagnetic pole elements of annular rotor and is defined by known expression:

$$W_K = 0,5 j\Omega^2. \qquad (11)$$

Substituting the meanings of kinetic energy of rotational motion in the Lagrange differential equation (11) and solving it, we get the general expression of moments energy balance for electromechanical system:

$$M_p = M_e + J\frac{d\Omega}{dt}. \qquad (12)$$

That is in the mode of generator the source of mechanical energy is rotor mechanical torque M_p which is defined by given lumped systems parameter and wind velocity as follows:

$$M_\text{p} = P/\Omega = 0.125\pi D^2\rho V_\text{в}^3 C_\text{p} D/(2ZV_в)$$
$$= 0.0625\pi D^3\rho C_\text{p} Z^1 V_\text{в}^2 \qquad (13)$$

If expressions for moments (9) and (13) are substituted in general equation (12), left only expression of electromagnetic torque on the right hand from sign of equality then we will receive the general mathematical movement of model conservative aero-electromechanical macrosystem according to lumped parameters location on the scheme (Fig. 2) as the balance of mechanical, dynamic and electromagnetic moments.

$$0.0625\pi D^3\rho V_\text{в}^2 C_\text{p} Z^{-1} - jd\Omega/dt = 0.5I^2 w^2 d\Lambda/d\varphi. \qquad (14)$$

Analyzing the mathematical expression of moments balance it can be argued that all three components, under known lamped parameters are dependent on wind speed, and electromagnetic torque can be defined both through the parameters of the magnetic field and the parameters of the circuit. This energy moments balance of macrosystem is depicted by structural algorithmic scheme of stages subordinated sequence of species and parametric energy transformations (Fig. 3).

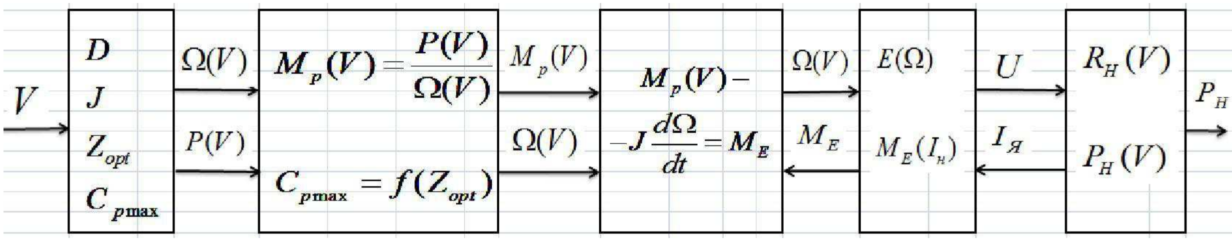

Fig. 3 Structural algorithmic scheme of aero-electromechanical macrosystem energy balance

This structural algorithmic scheme can be used as a general mathematical model of wind energy electromechanical conversion processes by different types of generators and adjustable power consumption. For generators of various types it will be differed only some parameters of magnetic system, which reflect the physical principles of electromagnetic interaction in electromechanical system that will determine the methods of power load adjusting.

One of the technical problems should be considered a fundamental difficulty of power generation increase with cubic dependence on wind speed, since rotated speed WT in this case changes linearly, and reserves of quadratic increase of generator electromagnetic torque are limited by allowable values of magnetic induction. From literature it is known that in the world such problems of electromechanical wind generator systems are solved by weakly rational way of two- and three-machine complexes use when only one generator works at the lower speed range of wind speed and under wind flow speed increasing it is sequentially connected backup generators in mode of parallel operation. Thus there are reasons to consider the problem described in this issue, which requires a more rational solution by principle new methods. To this purpose it was proposed a bi-packet inductor generator [7], in which separate independent stator modules various quantities are installed on the annular rotor of large diameter that permits to significantly expand the boundaries of power control single machine gearless wind turbine.

Besides, this type of generator allows to realize the cascade method of converting mechanical energy into electrical energy [8] by establishing not only a different number, but different types of stator modules with cascade principle of electromagnetic torque increase, a balanced the annular rotor by mechanical moment.

For researches of adaptive control regimes of experimental wind turbine with the switching principle of power generator change it has been developed a fundamental switching circuit of two load groups and measuring devices (Fig. 4).

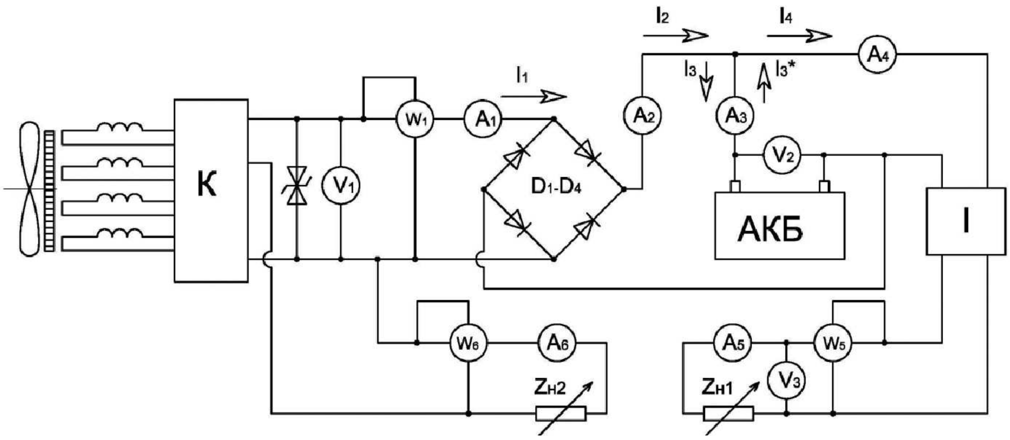

Fig. 4. Principle scheme adaptive control electrical complex with measurement devices and two different maintenance schedules channels of energy consumption

In experimental researches such principal circuit of the electrical equipment switching permits to determine the energy parameters simultaneously in all parts of the electro technical complex under different combinations of generate power and the value and nature of loads. The variable load $Z_{н1}$ models the stochastic principle of consumers' connection of industrial and household types, and other – $Z_{н2}$ is energy-salvaging load, which in [6] is substantiated to choose electrothermal type. The battery pack serves not only as energy storage, but the buffer load to maintain the acceptable values of input voltage inverter. As used switching principle of control, the protection against switching currents is provided via suppressor VD5. The whole system is controlled by programmable controller *K*.

CONCLUSIONS

1. To develop a model of adaptive control system of autonomous wind turbine should be used a scheme of electromechanical power conversion with strength function given the only parameter of wind speed under the constant parameters of air environment.

2. Analysis of mathematical model of aero-electromechanical conservative macrosystem permits to determine the principles of power generation increasing with cubic dependence on wind speed.

3. A bi-batch type of inductor generator with ring rotor allows technically implement the principle of generation power increasing of one machine complex by switching of different number stator modules and also the application of cascade method.

4. The principle scheme of WT adaptive system with different types of load groups permits to control the necessary parameters for different modes of operation.

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В. М. Синєглазов, В. В. Козирський, М. І. Трегуб, О. С. Василенко. Обґрунтування адаптивної самоналагоджувальної системи керування автономної вітроелектричної установки

Розглянуто принципи проектування адаптивної системи керування безредукторної електричної вітрової турбіни з максимальним коефіцієнтом потужності вітряних турбін для змінної швидкості вітру.

Ключові слова: автономна вітроенергетична система; алгоритми адаптивного керування і регулювання.

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В. М. Синеглазов, В. В. Козырский, Н. И. Трегуб, А. С. Василенко. Обоснование адаптивной самонастраивающейся системы управления автономной ветроэлектрической установки

Рассмотрены принципы проектирования адаптивной системы управления безредукторной электрической ветровой турбины с максимальным коэффициентом мощности ветряных турбин для переменной скорости ветра
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