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DEVELOPMENT OF THE CONTROL SYSTEM FOR TAKING OFF THE MAXIMUM POWER OF AN AUTONOMOUS WIND PLANT WITH A SYNCHRONOUS MAGNETOELECTRIC GENERATOR

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The object of this study is electromechanical processes in an autonomous wind power plant with a magnetoelectrical generator.

Under actual conditions, the wind speed is constantly changing. The wind turbine works as efficiently as possible only at the rated value of wind speed. When the wind speed changes, the efficiency of converting mechanical wind energy into electrical energy decreases. Controlling the power of the electric generator when the wind speed changes is a relevant scientific and technical task.

A maximum power selection control system based on the parameters of an experimental sample of a synchronous magnetoelectric generator has been designed and investigated. A feature of the synthesized control system is that it was developed on the basis of the concept of inverse dynamics problems in combination with minimization of local functionals of instantaneous energy values. The control law provides weak sensitivity to parametric perturbations of the object and carries out dynamic decomposition of the interdependent nonlinear system, which predetermines its practical implementation. Transient processes of the power, voltage, and current of the stator, as well as the voltage and excitation current were established when the wind speed changes from 3 to 8 m/s, as well as when the active electrical resistance of the load changes.

The results of this study confirm the effectiveness of the maximum power take-off control system when wind speed and load change. When the wind speed changes within 3–8 m/s and the load by 50 %, the efficiency of converting mechanical wind energy into electrical energy increases by 15–40 % compared to the traditional magnetoelectric system.

The findings of the current study are recommended for practical use in autonomous power plants based on wind turbines with generators with permanent magnets

Keywords: autonomous wind power plant, power control, synchronous magnetoelectric generator, instantaneous energy

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1. Introduction

Autonomous wind turbines are actively used to power remote buildings and structures. A typical power supply system consists of a wind turbine, a battery unit, a battery charge controller, and an inverter, which enables the required amplitude and frequency of the consumer's voltage.

As electric generators of wind turbines, the most widespread are three-phase synchronous generators with permanent magnets (Permanent Magnet Synchronous Generator (PMSG)), which have high technical and economic indicators. The main disadvantage of these generators is the lack of effective methods for controlling magnetic flux, which limits the optimization of the energy balance of the wind turbine.

During the operation of the wind turbine, the wind speed and, accordingly, the amount of electricity generated change. The power of the wind flow in the cube depends on the wind speed. The mechanical characteristic of the wind turbine has a point of maximum power. It is very important to solve the problem of selecting the maximum turbine power under conditions of changing wind speed.

High-quality control over the coordinates of the synchronous generator is also associated with resolving several more issues. The rechargeable battery, as the electrical load of the synchronous generator of the wind installation, is a nonlinear element. The magnitude of the internal resistance of the battery depends on the level of its charge. Another problem is caused by parametric perturbations. During the operation of the generator, its temperature changes and, as a result, the values of the electrical resistances of its windings change. The output values of the generator parameters may be inaccurately calculated, which is due to the errors of the corresponding procedures. Another issue is due to

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coordinate perturbations since the synchronous generator is described by an interdependent system of differential equations.

Solving these problems by classical methods of the theory of automatic control leads to the introduction of additional systems of identification, adaptation and/or compensation, which increases the cumbersomeness of the system as a whole.

A relevant scientific and practical area is the study of the efficiency of converting mechanical wind energy into electric energy by an autonomous wind power plant based on a magnetoelectric synchronous generator. One of the proposed methods is to use an additional generator excitation winding. This work aims to evaluate the effectiveness of this approach.

2. Literature review and problem statement

In [1], a hybrid system is investigated, which includes a wind power plant with a synchronous generator with permanent magnets. The system works through a converter on rechargeable batteries. An autonomous wind energy conversion system is used as a load. However, the flow of wind is inherently intermittent. In order to ensure the continuous supply of electricity, the authors proposed a system for accumulating energy in powerful batteries. This system is used as a backup system, activated when there is an excess or shortage of wind flow. A system for controlling the charge and discharge of the battery is proposed to ensure an effective balance of mechanical and electrical power. Despite the effectiveness of this approach, the implementation of the proposed method of controlling the initial parameters is complex and expensive.

In [2], a control scheme for an autonomous wind energy conversion system is proposed. This system is used to provide both autonomous systems and to work in parallel with the network. To ensure a continuous supply of electricity, a backup electricity storage device is used. The stability of a 4-kW wind power system with a backup drive has been investigated. As a load, an autonomous DC load with a capacity of 3 kW, representing the base telecommunications station, was used. The disadvantage of using the proposed system is insufficient maneuverability and limitations on the maximum possible power of the output load.

Paper [3] reports the design and simulation of a fuzzy proportional integral (Fuzzy-PI) controller used to maximize energy transmission by an autonomous wind energy conversion system. If one uses the Fuzzy-PI controller as part of an autonomous wind turbine, it improves system performance compared to the classic PI controller. The use of the proposed controller makes it possible to obtain improved results by adjusting the speed of the rotor of a synchronous generator with permanent magnets when the wind speed changes. The simulation results in the MATLAB/Simulink environment, presented by the authors in the work, show the effectiveness and good characteristics of the proposed developed system. However, how to practically implement the system for changing the speed of rotation of the rotor when the wind speed changes is unknown.

Study [4] describes the H-method of controlling wind turbines at a variable wind speed, which is below the rated, and under partial load. At wind speeds below rated, control objectives are to maximize energy conversion and minimize dynamic loads. The H-method of control is based on the boundary of the nonlinearity sector to combat noise, which affects the measurement of rotor speed and aerodynamic perturbations. The simulation results show that the proposed H-controller guarantees reliable operation and responds quickly to changes in wind speed to track the optimal rotor speed. Maximum efficiency can be achieved by constantly adjusting the rotor speed and updating the generator load to maximize power and reduce transmission torque transient loads. However, the disadvantage of such a system is the complexity of implementation, a complex control algorithm, and the expensiveness of the final product.

The control system of a multipolar gearless synchronous generator is described in [5]. Such systems are among the most promising for high-power wind turbines due to their high efficiency. In the cited paper, a wind turbine generation system is proposed on a basis with a simple diode rectifier using a system for compensating the magnetic energy of the generator when the load changes. Although the diode rectifier is simpler, more reliable, and inexpensive than an active rectifier, the diode rectifier itself is not capable of controlling reactive power. That is, in that paper, a wind energy conversion system with a diode rectifier and a magnetic energy compensation system is proposed. This system functions as a variable capacitor and makes it possible to control the torque of the generator, so that the maximum power when the wind changes, is realized by the control of the capacitors. However, the range of regulation of the output power of such a system is only 5–12 %, which is ineffective. In addition, powerful capacitors are an expensive element of such a system.

In [6], a hybrid system with a wind turbine and solar panels is considered in parallel operation of the system on the grid. The hybrid wind energy storage unit consists of a battery and a supercapacitor module. The effectiveness of various combinations of additional relationships and damping is shown, which makes it possible to form the necessary energy flows inside a closed system. This makes it possible to provide the desired management results. Among these tasks are the task of maintaining the voltage on the DC bus and the supercapacitor module at the reference levels, and the smoothness of the transients of the battery current. Comparative simulation studies were carried out on a computer model of the energy complex with synthesized control systems created in the MATLAB/Simulink environment. On the other hand, the efficiency of such a system is not shown offline and at low wind speed values.

Obtaining the parameters and characteristics of a synchronous machine with permanent magnets in the composition with a wind turbine according to the results of a previously carried out field electromagnetic calculation is shown in [7]. The results are established using the finite element method. The software package contains a computer simulation model of a synchronous generator with mechanical load. The model is built taking into consideration the magnetic saturation relative to the axis d and the axis q of the rotor. The mechanical load of the generator is set for each point of the mechanical characteristics of the wind turbine separately. This increases the complexity and time of modeling and does not make it possible to fully take into account the change in the rotor parameters of the wind turbine when the generator load changes.

The method of increasing the accuracy and reducing the sensitivity of the parameters of the wind generating installation based on the multicriterial synthesis of nonlinear robust control with two degrees of freedom is shown in [8]. The synthesis of nonlinear robust controllers and nonlinear robust observers is reduced to solving the Hamilton-Jacobi-Isaacs equations. The vector of the goal of robust control is determined on the basis of solving the problem of multicriterial nonlinear programming. The vector of the objective function is indicators of the efficiency of converting mechanical wind energy into electrical energy. This vector objective function is calculated when modeling a synthesized system under different modes of operation with different input signals and for different values of the parameters of the control object. The operation of the system at maximum peaks of the mechanical power of the wind turbine has not been investigated.

The problem of controlling the output parameters of the autonomous wind energy conversion system with a battery is considered in [9]. The system consists of a serial connected synchronous generator with permanent magnets, an uncontrollable rectifier, a transducer, a lithium-ion battery, and a DC load. The intermittent nature of the wind flow, as well as frequent changes in the load, reduce the battery life and reduce the performance of its charging. Depending on the available wind energy, battery charge status and DC load, three charging modes are adapted. Charging mode with tracking of the maximum power point, DC charging mode, and DC voltage charging mode. To ensure uninterrupted operation of the battery, the authors have developed a new algorithm for managing battery energy, to work under one of three modes, taking into consideration weather conditions and load changes. The advantage of the proposed method is that there is no need for sensors of battery status or wind speed. The cost of the system and the need for individual configuration of parameters is a significant drawback of the proposed system.

A new strategy for energy control and intelligent power management of an autonomous power generation system is described in [10]. It consists of a wind turbine with a synchronous generator with permanent magnets, a battery system, and a DC load. According to various climatic changes, load fluctuations and battery charge state, the examined one is considered as switching and indefinite nonlinear system. The main tasks are to regulate the amount of wind energy in order to realize the required power and maintain battery power to continue its cycle. An integrated sliding mode controller and an intelligent control method have been developed to improve the reliability and stability of the autonomous system in the case of strong disturbances. The proposed control system provides faster transient performance and lower rates of established errors compared to other methods presented. However, it is difficult to implement and does not take into consideration the presence of an additional magnetizing winding.

It is evident that magnetoelectric systems used as part of wind generating systems have obvious advantages. These include no losses on excitation, lack of a contact system, compared with generators with electromagnetic excitation. In addition, the well-known methods of regulating the output parameters of an electrical generating system based on a wind turbine with a synchronous generator do not fully show the effectiveness of using an additional magnetizing winding. Given this, it is necessary to conduct an assessment for the operation of the system when using a magnetizing winding with the maximum possible potential wind energy.

3. The aim and objectives of the study

The aim of this study is to design an automatic control system for the maximum power of an autonomous wind turbine with a synchronous magnetoelectric generator under conditions of changing wind speed and load, which will make it possible to increase the efficiency of converting mechanical wind energy into electrical energy.

To accomplish the aim, the following tasks have been set:

– to develop a functional diagram of the automatic control system with the maximum power of an autonomous wind turbine;

– to synthesize a mathematical model of a synchronous magnetoelectric generator;

– to synthesize control laws based on the method of inverse dynamics problems in combination with minimization of local functionals of instantaneous values of energies;

– to study the quality of adjustment of the automatic control system with the maximum power of an autonomous wind turbine under conditions of changes in wind speed and load.

4. The study materials and methods

The object of this study is electromechanical processes in an autonomous wind power plant with a magneto-electrical generator.

To take off the maximum power of a wind power plant with a magnetoelectric generator, it is necessary to control the working magnetic flux depending on changes in wind speed and load.

Mechanical processes proceed more slowly than electromagnetic processes in the generator. Electromechanical time constants are much longer than electromagnetic ones.

Magnetoelectric synchronous generators are electric generators in which permanent magnets are used to induce the main magnetic flux. This paper proposes the design of a magnetoelectric generator with hybrid excitation. An additional winding (magnetizing winding) can enhance or weaken the magnetic flux.

These generators combine the advantages of traditional generators with electromagnetic excitation and high-power density, simplicity, and reliability of generators with permanent magnets. The power range of synchronous magnetoelectric generators for autonomous wind turbines within kilowatts or tens of kilowatts is considered.

Wind speed is variable, which causes a change in the speed of rotation and the mechanical power of the wind turbine. Plots of the dependence of the output power of the turbine on the wind speed have three areas of control of the wind generator; they are shown in Fig. 1. The study of automatic control of the wind turbine during operation in the second zone at a variable speed of rotation of the wind turbine shaft was carried out in the current work.

To control the magnetic flux of a synchronous generator, synchronous generators with hybrid excitation can be used. The excitation system consists of permanent magnets on the rotor and an electric excitation winding located on a fixed stator [12]. The main magnetic flux is created by permanent magnets, and on average about 20 % – by the excitation winding. The magnetic flux of the generator is controlled by changing the current of the excitation winding. Of particular note are designs with an axial magnetic flux [12], which provide low synchronous speeds of rotation. This makes it possible to obtain a direct (gearless) connection between the windmill and the generator. This design is promising for use in autonomous wind energy systems as it makes it possible to expand the range of adjustment and increase the efficiency of converting wind energy into electrical energy. The structure of a magnetoelectric generator with an axial magnetic flux is shown in Fig. 2.

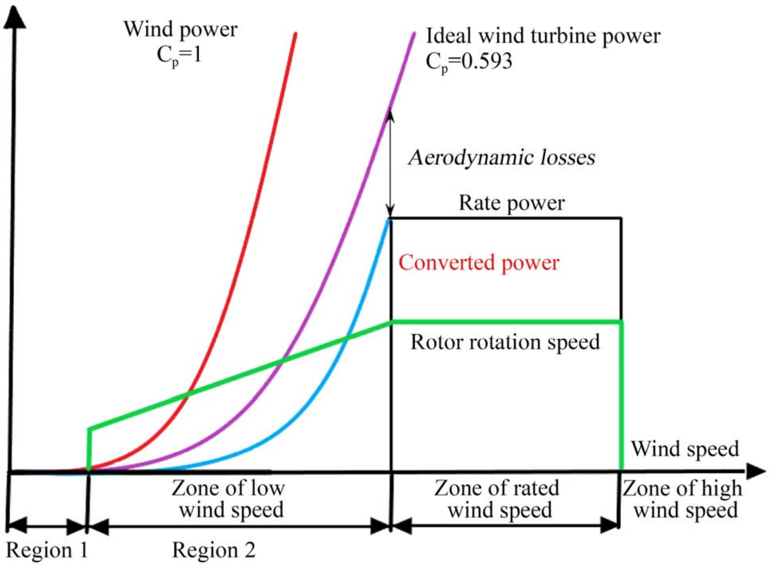


Fig. 1. Turbine output power depending on wind speed

A synchronous electrical machine by its nature, like other types of AC machines, is an interdependent nonlinear control object, and with the influence of eddy currents. Control over a synchronous machine under such conditions requires compensation for the negative impact of these coordinate perturbations. When determining the parameters of the synchronous machine replacement scheme based on the passport data, errors arise due to the assumptions of the calculation methodology. During the operation of the machine, the electrical resistances of the windings change due to heating. As a result of these parametric disturbances, the calculated values of the parameters differ from the real ones, which leads to a deterioration in the specified quality of control.

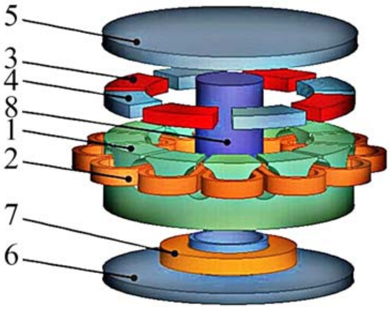


Fig. 2. Synchronous generator with axial magnetic flux: 1 – magnetic stator core made of rolled electrical steel; 2 – copper single-layer three-phase stator winding; 3 – permanent magnets; 4 – pole cores, the shape and size of which are identical to permanent magnets; 5 – rotor inductor, which enables the flow of magnetic flux; 6 – ferromagnetic hub; 7 – excitation winding; 8 – generator shaft [13]

This type of synchronous magnetoelectric generator is taken as the basis for research in this paper.

It is possible to solve the problem of synthesis of the laws of control of the coordinates of a synchronous generator under conditions of parametric and coordinate perturbations by several methods from the theory of automatic control:

1. Relay control methods with a variable structure ensure the operation of controllers under a relay mode. This feature causes the appearance of characteristic sliding modes of operation. Sliding modes increase energy consumption for control and lead to increased wear of mechanisms, reduce noise immunity of the system and can lead to unstable operation due to unaccounted-for dynamics. To reduce these shortcomings, relay elements are replaced by linear units with saturation, resulting in smoothed methods with a variable structure. Systems based on them are close to relay ones in dynamic characteristics but develop limited control actions, which impairs control accuracy and robustness.

2. Control methods with a large gain of an open system have increased accuracy and robust stability in relation to the uncertainty of parameters and external low-frequency influences. However, with large coefficients, the appearance of instability of high-frequency unaccounted-for dynamics is possible, as well as the appearance of errors due to high-frequency interference.

3. Combined control methods with uncertainty observers allow for a nonlinear non-stationary object to synthesize a linear stationary controller that provides specified indicators of control quality. In this method, the tasks of compensating for external influences and ensuring specified quality indicators of transients are solved independently, which simplifies synthesis. The disadvantage of the method is the difficult conditions for ensuring the efficiency of the observer of uncertainty.

4. Adaptive control methods with real-time parameter identification are mainly designed for linear systems. Their capabilities are limited with an increase in the number of parameters due to the need to meet the conditions for their identification, determined by the nature of the movement. This leads to an increase in requirements for the nature of the movement of the system, which may not correspond to the technological process. In adaptive control methods with a reference model, the model of the desired movement is determined in the form of equations with initial conditions closest to the initial conditions of the control object. Since the control system must track a given trajectory, the equations of motion are represented in the form of two components: the equations of the reference model and the equations of motion according to this model. For complex objects, the equations of motion will be nonlinear and non-stationary. This circumstance complicates both the synthesis of control algorithms and the study of the stability of the trajectory.

5. The method of inverse dynamics problems in combination with minimization of local functionals of instantaneous values of energies is based on the idea of reversibility of the direct method of Lyapunov regarding the study of stability. The method makes it possible to find the law of control in which a closed loop has a predetermined Lyapunov function. This gives the system the property of stability as a whole, which makes it possible to solve problems of controlling interdependent objects according to mathematical models of local contours. A characteristic feature of optimization is finding not an absolute mini-

mum of quality functionality, as in classical systems, but a certain minimum value that provides a dynamic error of the system permissible by technical conditions. The established control laws provide weak sensitivity to parametric perturbations, carry out dynamic decomposition of an interconnected system and do not contain differential links, which enables their practical implementation. The specified advantages of the method predetermine its use in this work.

The development of an automatic control system for the maximum power of an autonomous wind turbine with a permanent magnet synchronous generator (PMSG) is considered on the example of an experimental sample of a synchronous generator with an axial magnetic flux that we designed. The general view of the experimental PMSG is shown in Fig. 3.

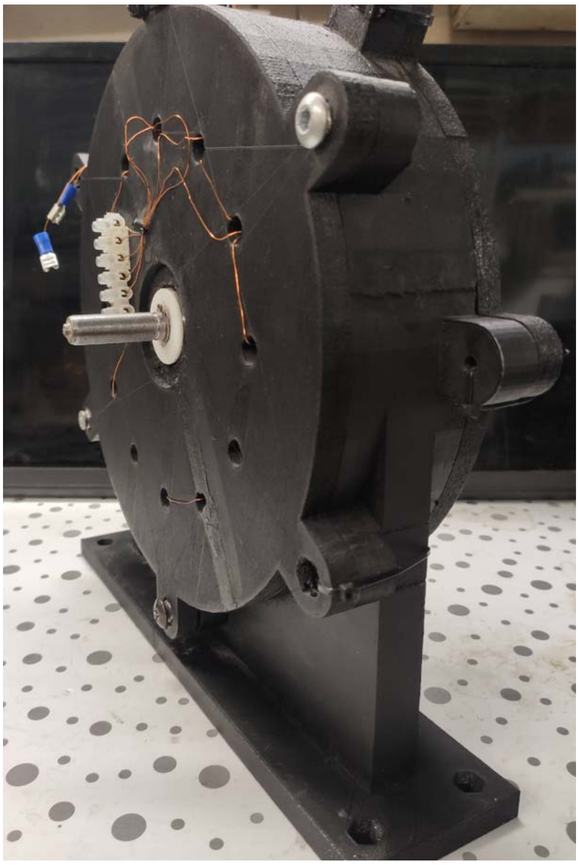


Fig. 3. General view of the experimental generator

The main parameters of the experimental PMSG are given in Table 1.

For experimental PMSG, the dependence of mechanical power on the speed of rotation of the rotor of the wind turbine with a change in wind speed from 3 to 8 m/s is calculated. The calculation results are shown in Fig. 4. As can be seen in Fig. 4, at any value of the speed of rotation there are extreme points on the characteristics that form the curve of the maximum output power of the wind turbine $P_{\max}$.

The curve $P_{\max}$ (Fig. 4) reflects the maximum mechanical and electrical power that the wind turbine generates when the wind speed changes. For the most efficient conversion of wind mechanical energy into electrical, the task of the control system is to operate the generator according to this curve.

Table 1

Parameters of the experimental PMSG

No.	Parameter	Value
1	Full rated power, VA	86.0
2	Nominal phase voltage, V	24.0
3	Nominal phase current, A	1.2
4	The number of pairs of poles	4
5	Nominal phase resistance of the stator winding, Ohm	8.8
6	Phase inductance of the stator winding, N	0.022
7	Resistance of additional winding, Ohm	8
8	The inductance of the additional winding, N	0.017
9	Rated voltage of the additional winding, V	8
10	Rated current of the additional winding, A	1
11	Magnetic flux of permanent magnets, Wb	0.16

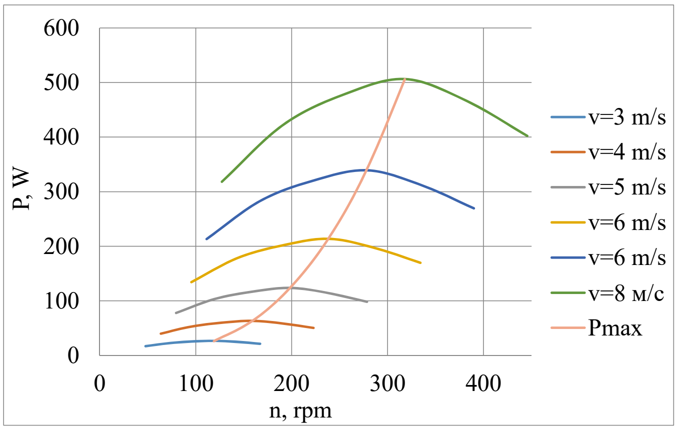


Fig. 4. The dependence of mechanical power on the speed of rotation of the wind turbine for an experimental generator

5. Results of studying the power control system for an autonomous wind installation with a synchronous magnetoelectric generator

5. 1. Design of a functional diagram of the automatic control system for the maximum power of an autonomous wind turbine

The automatic control system has a cascading structure. It consists of an internal circuit for regulating the excitation current i_f and an external circuit for regulating the maximum electrical power of the generator P. In the process of control, PMSG loads the wind turbine with torque T, ensuring operation at the point of extreme on the mechanical characteristic according to Fig. 4.

The functional diagram of the control system is shown in Fig. 5.

The task of the automatic control system is to take off the maximum power of the wind turbine at a certain wind speed. The implementation of the system is achieved by adjusting the excitation current of PMSG.

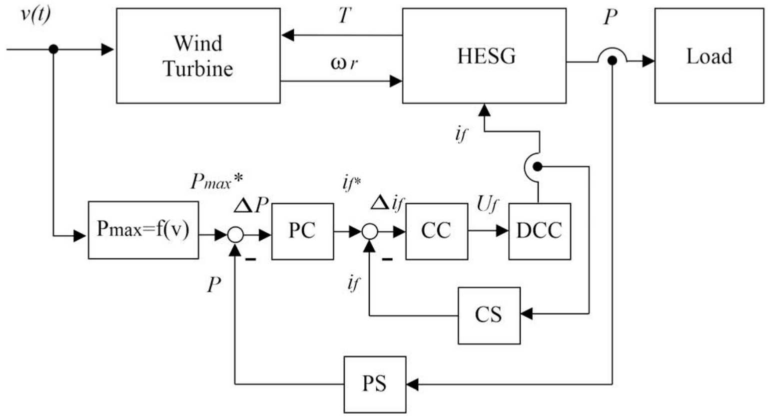


Fig. 5. Functional diagram of the wind turbine maximum power control system: PC — generator power controller; CC — generator excitation current controller; DCC — DC converter; CS — current sensor of additional excitation winding; PS — power sensor; $P^*_{\max}$, P — reference and measured value of active power; i^*_f, i_f — reference and measured value of the additional winding current

5. 2. Building a mathematical model of a synchronous magnetoelectric generator with hybrid excitation

The mathematical model of PMSG in the coordinate system (*dq*) oriented along the magnetic axis of the rotor is described by a nonlinear system of equations (1) [13]:

$$\begin{cases} \dfrac{di_d}{dt} = \dfrac{1}{L_s}\left[u_d - R_s i_d + \omega L_s i_q - L_m \dfrac{di_f}{dt}\right]; \\ \dfrac{di_q}{dt} = \dfrac{1}{L_s}\left[u_q - R_s i_q - \omega L_s i_d - \omega L_m i_f - \omega\psi_0\right]; \\ \dfrac{di_f}{dt} = \dfrac{1}{L_f}\left[u_f - R_f i_f - L_m \dfrac{di_d}{dt}\right]; \\ \dfrac{d\omega_r}{dt} = \dfrac{1}{J}\left[T_{WT} - T\right]; \\ T = \dfrac{3}{2} Z_p \left[\psi_0 i_q \pm L_m i_q i_f\right], \end{cases} \tag{1}$$

where i_d, i_q and u_d, u_q are the currents and voltages of the stator on *d*- and q-axes; i_f and u_f – current and voltage of the additional winding; $\omega = Z_p \cdot \omega_r$, and ω_r – electric and angular velocity of the rotor; Z_p – number of pairs of poles; J – moment of inertia; T, T_{WT} – electromagnetic moment and mechanical torque of the turbine; ψ_0 – magnetic flux of permanent magnets; L_s, L_f, L_m – inductance of the stator winding, additional winding and mutual inductivity; R_s, R_f – active resistance of stator windings and additional.

To solve the control problem, the initial system of equations (1) is converted to the form (2) by decomposition method. Coordinate perturbations F_1, F_2, F_3 are interpreted as non-defined but limited in magnitude $F_1 \le F_1^0$, $F_2 \le F_2^0$, $F_3 \le F_3^0$ to the level of control voltages sufficient to compensate for them $u_d > F_1^0$, $u_q > F_2^0$, $u_f > F_3^0$.

Thus, an interconnected nonlinear system of the 4th order is transformed into a system of 4 linear equations of the first order. As a result, the task of controlling the object (1) is reduced to solving four local control problems of linear subsystems (2).

$$\begin{cases} L_s \dfrac{di_d}{dt} + R_s i_d = u_d + F_1; \\ L_s \dfrac{di_q}{dt} + R_s i_q = u_q + F_2; \\ L_f \dfrac{di_f}{dt} + R_f i_f = u_f + F_3; \\ J \dfrac{d\omega_r}{dt} = \left[T_{WT} - T\right]; \\ T = \dfrac{3}{2} Z_p \left[\psi_0 i_q \pm L_m i_q i_f\right]; \\ F_1 = \omega L_s i_q - L_m \dfrac{di_f}{dt}; \\ F_2 = -\omega L_s i_d - \omega L_m i_f - \omega\psi_0; \\ F_3 = -L_m \dfrac{di_d}{dt}. \end{cases} \tag{2}$$

Thus, the mathematical model of PMSG is implemented by modifying building blocks with differential equations (2) in MATLAB-Simulink software.

5. 3. Control laws based on the method of inverse dynamics problems

The desired quality of the closed loop control according to the concept of inverse dynamics problems is given by the differential equation of the following type

$$\frac{d^n z}{dt^n} + .. + \gamma_i \frac{d^i z}{dt^i} + .. + \gamma_0 z = = \beta_m \frac{d^m x^*}{dt^m} + .. + \beta_j \frac{d^j x^*}{dt^j} + .. + \beta_0 x^*. \tag{3}$$

Using the coefficients of the equation γ_i and β_j, the desired nature and duration of the transient process of the initial coordinate z during the movement of a given trajectory x^* where x^* is the time differentiated function of the required number of times; $m<n$. The desired closed-loop control transfer function, established from equation (3) for the case $n=3$ and $m=1$, is (where $p=d/dt$ is the Laplace operator)

$$W_s(p) = \frac{z(p)}{x^*(p)} = \frac{\beta_1 p + \beta_0}{p^3 + \gamma_2 p^2 + \gamma_1 p + \gamma_0}. \tag{4}$$

The corresponding transfer function of the open control circuit is equal to

$$W_r(p) = \frac{W_s(p)}{1 - W_s(p)} = = \frac{\beta_1 p + \beta_0}{p^3 + \gamma_2 p^2 + (\gamma_1 - \beta_1)p + (\gamma_0 - \beta_0)}. \tag{5}$$

From equation (5) it follows that to obtain a control system with the first-order astatism $\nu=1$, it is necessary to set the value of the coefficients $\beta_0 = \gamma_0$, then

$$W_r(p) = \frac{\beta_1 p + \gamma_0}{p\left[p^2 + \gamma_2 p + (\gamma_1 - \beta_1)\right]}, \tag{6}$$

and with the second-order astatism $\nu=2$, one needs to set $\beta_0=\gamma_0$ and $\beta_1=\gamma_1$

$$W_r(p)=\frac{\gamma_1 p+\gamma_0}{p^2\left(p+\gamma_2\right)}. \tag{7}$$

The given quality at the speed of the system (6) is determined by the expression $D^z_\omega=\gamma_0/\left(\gamma_1-\beta_1\right)$, and the quality of the acceleration of the system (7) is equal to $D^z_\varepsilon=\gamma_0/\gamma_2$. Order n of equation (3) and the transfer function (4) can be different for each closed loop of control in accordance with the requirements for the quality of control and is usually equal to or one above the order of the control object.

The structure and parameters of the equation of the desired control quality (3) are set so that the perturbed motion is asymptotically stable. According to the Hurwitz stability criterion for the third-order equation, this condition is met at the ratios of the parameters $\gamma_0>0$; $\gamma_1>0$; $\gamma_2>0$; and $\gamma_1\gamma_2>\gamma_0$. For second and first-order equations – with positive values of coefficients.

The relationship between the coefficients of equation (3) and the necessary indicators of control quality, such as adjustment time, type of transient process, overshoot is easily established using well-known methods from automatic control theory. These are methods such as root, frequency, or the method of standard polynomials, refined by modeling.

The development of the excitation current control law i_f PMSG is carried out on the basis of the third equation of system (2). As can be seen, the local control object is described by the first-order equation, therefore the order of the desired closed-circuit equation of the current in the form (3) is also assumed to be equal to one ($n=1$; $m=0$) with the provision of the first-order astatism $\nu=1$ and a given quality at speed $D^z_\omega=\gamma_{0f}$

$$\dot z+\gamma_{0f}z=\gamma_{0f}i_f^*. \tag{8}$$

The duration of the monotonous current transient process $t_r\approx3/\gamma_{0f}$ is given using the value of a single coefficient γ_{0f}.

It is necessary to find such a control function of the excitation current controller u_f so that the quality of current control approaches the desired one given by equation (8). The degree of approximation of the real current control process to the desired one is estimated by the functional that characterizes the energy normalized by inductance of the first magnetic field derivative of the form $W_m=L\cdot(i^2/2)$.

$$G\left(u_f\right)=\frac{1}{2}\left[\dot z(t)-\dot i_f\left(t,u_f\right)\right]^2. \tag{9}$$

Finding the control function $u_f=u_f(i_f)$ by classical methods from the theory of automatic control under the conditions of achieving the absolute minimum of the functional leads to the traditional control law of the compensation type, the implementation of which requires accurate information about the structure and parameters of the object

$$\min_u G\left(u_f\right)=0. \tag{10}$$

Deviation of parameters from the calculated values leads to a deterioration in the quality of control.

This disadvantage is eliminated if one refuses to accurately fulfill condition (10) but only limits himself to the requirement that the value of functionality (9) belongs to some neighborhood of the extreme minimum. This provides for a technically acceptable dynamic error $|z(t)-i_f(t)|\le\varepsilon$. For this, the minimization of the functional is carried out according to the gradient law of the first order

$$\frac{du_f(t)}{dt}=-\lambda_f\frac{dG\left(u_f\right)}{du_f}, \tag{11}$$

where $u_f>0$ is a constant.

Taking into consideration (2) and (8), the derivative of the functional is equal to

$$\frac{dG\left(u_f\right)}{du_f}=-\frac{1}{L_f}\left(\dot z-\dot i_f\right). \tag{12}$$

After substitution (11), (12), we find the law of control of the excitation current

$$\dot u_f(t)=k_f\left(\dot z-\dot i_f\right), \tag{13}$$

where $k_f=\lambda_f/L_f=\text{const}$ is the gain of the excitation current controller.

The necessary condition for the convergence of the process of minimizing the functional according to $t\to\infty$ takes the form

$$\frac{dG\left(u_f\right)}{dt}<0; \tag{14}$$

$$G\left(u_f\right)\to 0.$$

This condition is fulfilled in accordance with the signs rule

$$\operatorname{sign}\left(k_f\right)=\operatorname{sign}\left(1/L_f\right). \tag{15}$$

The variable z in the control law (13) is the required (given) derivative of the excitation current n. It is determined in real time from the equation of the desired quality (8) by closing the feedback control system on the excitation current $z=i_f$

$$\dot z=\gamma_{0f}\left(i_f^*-i_f\right). \tag{16}$$

Finally, the law of motion control of the violation takes the form after integrating both parts of equation (13) taking into consideration (16)

$$u_f(t)=k_f\left(z-i_f\right); \tag{17}$$

$$z=\gamma_{0f}\int\left(i_f^*-i_f\right)\mathrm{d}t.$$

Based on (17), a block diagram of the excitation current controller (CC) of type 101 ($n=1$) was built; $m=0$; $\nu=1$, shown in Fig. 6.

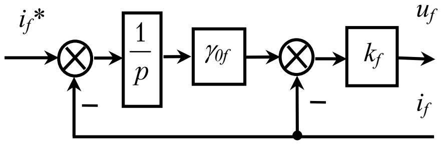


Fig. 6. The structure of the generator excitation current controller

Fig. 6 shows that the controller has an atypical structure and does not contain the parameters of the control object (2), which is typical for classical controllers. The controller contains only the parameter γ_{0f} of the desired control law (8), with the help of which the required time of the monotonous transient process is set.

An important task of synthesis is to study the stability of the established control system. The closed-loop equation of the excitation current established after substitution to the third equation of the object (2) of the law of control (13), taking into consideration (16) takes the form

$$\begin{aligned}&\ddot{i}_f+\left(R_f/L_f+k_f/L_f\right)\dot{i}_f+\left(k_f\gamma_{0f}/L_f\right)i_f=\\&=\left(k_f\gamma_{0f}/L_f\right)i_f^*.\end{aligned} \qquad (18)$$

The analysis shows that a closed system (18) is stable even with an unlimited increase in the gain of the current controller $k_f\to\infty$, since according to the Hurwitz stability criterion, the coefficients of the equation are positive

$$\left(R_f/L_f+k_f/L_f\right)>0;\ \left(k_f\gamma_{0f}/L_f\right)>0. \qquad (19)$$

With an increase in the gain of the controller, dynamic processes in the real circuit of the excitation current approach the desired one given by equation (8). This is obvious after dividing all the terms of equation (18) by a component k_f/L_f at $k_f\to\infty$

$$\frac{L_f}{k_f}\ddot{i}_f+\left[\frac{R_f}{k_f}+1\right]\dot{i}_f+\gamma_{0f}i_f=\gamma_{0f}i_f^*. \qquad (20)$$

In the excitation current control circuit, there is a small time constant T_μ of the DCC power converter, which was not taken into consideration during the synthesis of the control law. Assessment of the effect of this unaccounted-for inertia on the dynamic properties of the excitation current circuit is carried out using a closed system equation established similarly (18)

$$\begin{aligned}&T_\mu\dddot{i}_f+\left(1+T_\mu R_f/L_f\right)\ddot{i}_f+\\&+\left(R_1/L_f+k_f/L_f\right)\dot{i}_f+\left(k_f\gamma_{0f}/L_f\right)i_f=\\&=\left(k_f\gamma_{0f}/L_f\right)i_f^*.\end{aligned} \qquad (21)$$

According to the Hurwitz criterion, for the stability of the current circuit described by equation (21), the following condition is required.

$$\left(1+T_\mu R_f/L_f\right)\left(T_\mu R_f/L_f+k_f/L_f\right)>T_\mu k_f\gamma_{0f}/L_f, \qquad (22)$$

which is converted to the next inequality as a result of the boundary transition

$$\gamma_{0f}<1/T_\mu+R_f/L_f. \qquad (23)$$

Thus, the presence in the excitation current control circuit of a small time constant T_μ limits the maximum allowable desired speed of the current circuit set by the coefficient γ_{0f}.

An important issue is to determine the properties of the excitation current circuit at the finite values of the gain of the controller k_f. The transfer function of the open current circuit, established on the basis of (18) similar to (5), takes the form

$$W_r(p)=\frac{k_f\gamma_{0f}/L_f}{p\left[p+\left(R_f/L_f+k_f/L_f\right)\right]}. \qquad (24)$$

According to (24), the current circuit has a given astatism of the first order ν=1 and the quality at a speed equal to

$$D_\omega=\frac{k_f\gamma_{0f}/L_f}{R_f/L_f+k_f/L_f}=\frac{\gamma_{0f}}{R_f/k_f+1}. \qquad (25)$$

The condition for ensuring the permissible dynamic current error is the commensurate given and real quality $D_\omega^z=D_\omega$, performed according to (25) with a large gain of the controller k_f.

This disadvantage is excluded if we synthesize the law of control based on the equation of the desired quality, the order of which is n=2. Unlike (8), it is unity higher than the order of the equation of the local control object – the third equation of system (2):

$$\ddot{z}+\gamma_{1f}\dot{z}+\gamma_{0f}z=\gamma_{0f}i_f^*. \qquad (26)$$

Applying the above procedure, the following law of control of the excitation current is established

$$\begin{aligned}&u_f(t)=k_f\left(z-i_f\right);\\&z=\int f_0\mathrm{d}t;\\&f_0=\gamma_{0f}\int\left(i_f^*-i_f\right)\mathrm{d}t-\gamma_{1f}i_f.\end{aligned} \qquad (27)$$

According to equation (27), a block diagram of the excitation current controller (CC) of type 201 is constructed, shown in Fig. 7. The controller also does not contain the parameters of the control object, which is inherent in classical laws.

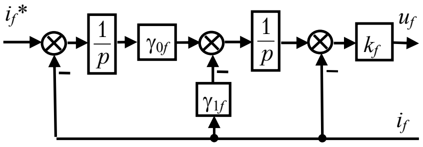


Fig. 7. The structure of the generator excitation current controller

The transfer function of the open current circuit for this control law is

$$W_r(p)=\frac{k_f\gamma_{0f}/L_f}{p\left[p^2+\left(R_f/L_f+k_f/L_f\right)p+k_f\gamma_{1f}/L_f\right]}. \qquad (28)$$

According to (28), the current circuit has a given astatism of the first order ν=1 and quality at a speed equal to the specified

$$D_\omega=D_\omega^z=\frac{\gamma_{0f}}{\gamma_{1f}}. \qquad (29)$$

This provides a permissible dynamic current error at moderate gains of the controller k_f.

The development of the law of control of the maximum power P for PMSG is carried out on the basis of the desired closed-loop equation of the first order (n=1; m=0) with the provision of the first-order astatism ν=1 and a given quality at speed $D^{z}_{\omega}=\gamma_{0p}$

$$\dot{z}+\gamma_{0p}z=\gamma_{0p}P^{*}_{\max}. \qquad (30)$$

The duration of the monotonous transient process of power $t_r \approx 3/\gamma_{0p}$ is set using the value of the coefficient γ_{0p}. After the synthesis of the control law, carried out similarly to the above synthesis of excitation current, the following equation of the power controller is derived.

$$i_f^{*}(t)=k_p(z-P); \qquad (31)$$

$$z=\gamma_{0p}\int\left(P^{*}_{\max}-P\right)\mathrm{d}t.$$

Based on (31), a block diagram of the maximum power controller (PC) of type 101 is constructed, shown in Fig. 8.

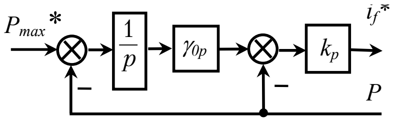


Fig. 8. The structure of the generator maximum power controller

The power controller has an atypical structure and does not contain the parameters of the control object (2), which is typical for classical controllers. The controller contains only the parameter γ_{0p} of the desired control law (30), with the help of which the required time of the monotonous transition process is set.

5. 4. Investigating the quality of regulation of the automatic control system with the maximum capacity of an autonomous wind turbine

We studied the quality of control over the developed system by modeling in the MATLAB/Simulink environment with the parameters of experimental PMSG given in Table 1. Excitation current and maximum power controllers have the following parameter values: γ_{0f}=1000; k_f=1000; γ_{0p}=500; k_p=0.1.

During the simulation process, the wind speed varied from 3 to 8 m/s, as shown in Fig. 9.

The control system calculates the maximum output power of the wind turbine rotor depending on the wind speed (Fig. 9), which is the task signal for the output power control circuit of the electric generator.

Due to the operation of excitation current and power controllers, the PMSG produces the maximum electrical power per load (the curve repeats the shape, as shown in Fig. 10).

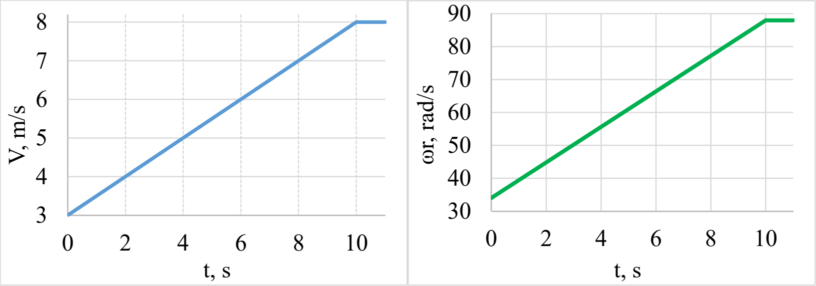
The current and voltage plots of the additional excitation winding during the control process are shown in Fig. 11.

The plots of current and voltage on the PMSG stator with changes in wind speed and load are shown in Fig. 12.

An important issue is the study of the quality of transients in squally winds and a sudden change in load. Fig. 13 shows a plot of the excitation current, and Fig. 14 – a maximum power plot with an increase in wind speed jump from 3 to 8 m/s.

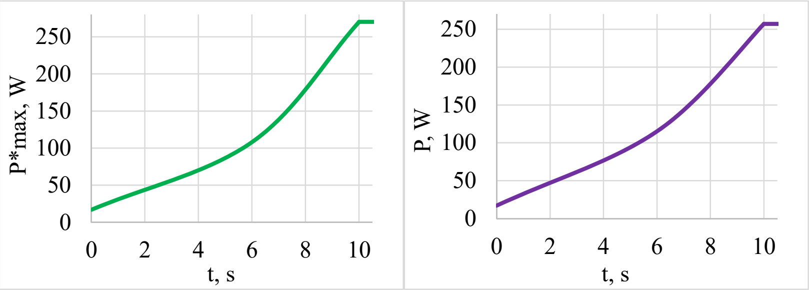
Fig. 15 shows a plot of the excitation current and a plot of the maximum power when changing the electrical resistance of the generator load in a jump.

After the transient process, the current and power stabilize and remain unchanged, this indicates the stability of the control system.



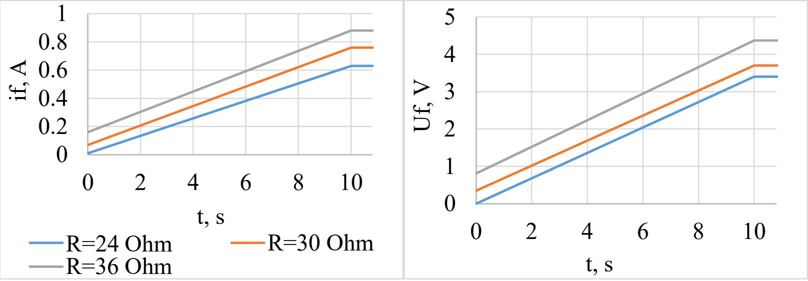
a *b*

Fig. 9. The nature of the change in wind and speed of rotation: *a* — the plot of changes in wind speed; *b* — the plot of change in the speed of a synchronous magnetoelectric generator



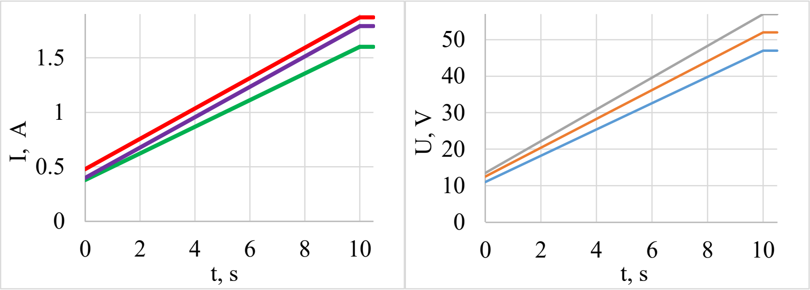
a *b*

Fig. 10. The nature of the power change: *a* — the plot of the maximum power of the wind turbine rotor; *b* — the plot of electric power of the generator



a *b*

Fig. 11. Electrical parameters of the additional winding: *a* — current of the additional winding; *b* — voltage of the additional winding



a *b*

Fig. 12. Electrical parameters of the generator armature winding: *a* – generator stator current; *b* – generator stator voltage

6. Discussion of results of controlling the maximum power of an autonomous wind installation with a synchronous magnetoelectric generator

The functional diagram of the automatic control system with the maximum power of an autonomous wind turbine (Fig. 5) consisting of PMSG with an axial magnetic flux has been developed. The system changes the current of the additional winding of the generator in such a way as to operate at the maximums of the output mechanical power of the wind turbine (Fig. 4) when the wind speed changes. The reference data are the speed of rotation of the rotor of the wind turbine and the maximum power values.

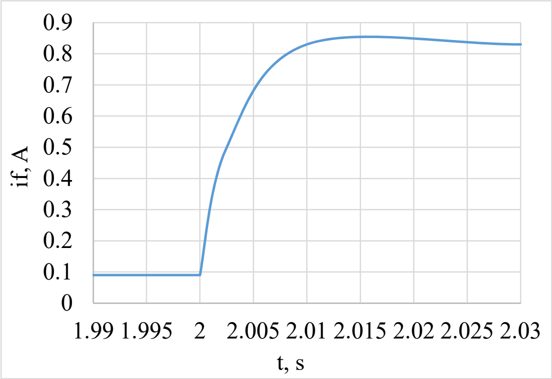


Fig. 13. Plot of the transient process of excitation current when the wind changes

When the wind speed changes from 3 to 8 m/s (Fig. 9, *a*), the angular velocity of the PMSG rotor varies from 34 to 86 rad/s, respectively (Fig. 9, *b*). According to these data, the control system (Fig. 5) calculates the maximum output power of the wind turbine rotor depending on the wind speed (Fig. 4, 9). Wind speed is a signal of the task for the correction circuit by the output power of the synchronous generator. When the excitation current (Fig. 7) and power (Fig. 8) controllers are operating, the generator outputs the maximum electrical power to the load (Fig. 10, *b*). Under the condition of a change in wind speed, the electric generator gives active power to the load from ≈20 W to 270 W at a wind speed of 8 m/s. This makes it possible to increase the efficiency of converting mechanical wind energy into electrical energy by 15–40 % [11, 13].

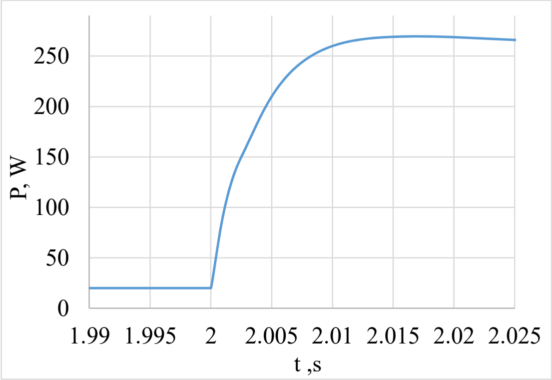
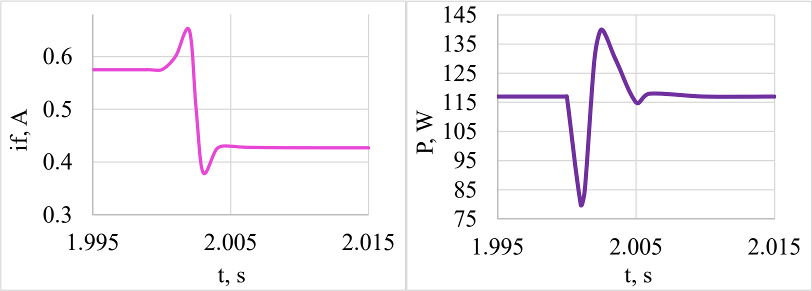


Fig. 14. Plot of the transition process of maximum power when the wind changes

According to the results shown in Fig. 11, *a*, *b*, the current and excitation voltage of the generator must be increased with increasing wind speed and reduced with increasing load: R_{load}=36 Ohm; 30 Ohms; 24 Ohms. In the first case, this is due to a significant increase in the mechanical power of the wind turbine rotor, and therefore the need to increase the magnetic flux of the generator to generate maximum power. In the second case, it is related to the aerodynamic parameters and characteristics of the rotor of the wind turbine and load parameters.

When the wind speed changes from 3 to 8 m/s, the current of the generator stator increases from 0.38 to 1.6 at a load of 36 Ohms and from 0.46 to 1.98 A at 24 Ohms (Fig. 12, *a*). At the same time, the voltage of the generator stator increases from 13.5 to 58.0 at a load of 36 Ohms and from 11 to 47 V at 24 Ohms (Fig. 12, *b*). The results shown in Fig. 11, 12 are achieved when adjusting the maximum power of PMSG.



a *b*

Fig. 15. The nature of transients in the system: *a* – the plot of the transient process of excitation current; *b* – the plot of the maximum power when changing the load

The plots of excitation current (Fig. 13) and maximum power (Fig. 14) are characterized by monotonous (without overshoot) transients during the time determined by the parameters of controllers γ_{0f} and γ_{0p} (3) to (30).

The plot of the excitation current and the plot of the maximum power when changing by a jump in the electrical resistance of the load from 36 to 24 Ohms at a wind speed of 6 m/s (Fig. 15) characterizes the stability of the developed system under a dynamic mode. After the transient process, the maximum power acquires a previous value of 117 W, and the excitation current decreases from 0.58 to 0.43 A.

Existing methods for correcting the output power of PMSG are based on the use of external step capacitive controllers. On the one hand, they load the generator with additional reactive capacitive current, on the other hand, they require a switching system, which complicates the design as a whole and reduces its reliability. The proposed system is devoid of these shortcomings, it makes it possible to smoothly adjust the output power in a given load range. It makes it possible to increase the efficiency of converting mechanical wind energy into electrical energy due to work at maximum power and does not cause additional losses in the armature winding.

The limitations of the proposed method are associated with limited limits of adjustment compared to systems with electromagnetic excitation. In addition, permanent magnets used in this PMSG have limitations on magnetic characteristics under elevated thermal conditions. In addition, the investigated synchronous magnetoelectric generator is more expensive than generators with excitation from permanent magnets by ≈15–20 %. Compared to the unregulated system, the implementation of the proposed maximum power control system will increase the total cost of the system (wind turbine, electric generator, converter, battery) by ≈0.05–0.07 %.

The disadvantages of correcting the output power of the wind turbine due to the use of the excitation current of the additional winding are associated with a higher cost of the PMSG compared to generators with permanent magnets. Also, with power losses in the PMSG winding, which can be up to 5 % of the generator power and the need for an additional winding control system.

The development of this study is in the area of manufacturing experimental samples of wind generating installations whose composition includes PMSG, which will increase the efficiency of converting mechanical wind energy into electrical energy. In addition, based on our result, several methods for correcting the output power of a synchronous generator follow, which can be described in the future.

7. Conclusions

1. A system of automatic control of maximum power selection based on the regulation of the working magnetic flux of a magnetoelectric generator by changing the current of the additional excitation winding has been developed. This makes it possible to increase the efficiency of converting mechanical wind energy into electrical energy. The control system consists of an internal excitation current control circuit and an external power control circuit.

2. The mathematical model of PMSG is synthesized in the coordinate system d–q. A feature of the implemented mathematical model is that the problem of controlling the generator is reduced to solving four local problems of controlling linear subsystems. This was achieved by transforming an interconnected nonlinear system of the 4th order into a system of 4 linear equations of the first order.

3. High quality control of power and excitation current is provided by the original control algorithms, which are developed on the basis of minimizing local functionalities of instantaneous values of electromagnetic energy. Control laws provide stability in parametric and coordinated perturbations, as well as ease of implementation of the controller. The system enables the absence of static control error, as well as the permissible dynamic error up to ≈18 % when changing the load surge and wind speed.

4. Our study of the control process of an autonomous wind power plant on the example of a prototype PMSG confirmed the high quality of regulation of the maximum power when the wind speed changes from 3 to 8 m/s and the load changes by 50 %.

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