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Electromechanical system with squirrel-cage induction generator for small-scale wind power plants

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Abstract: This work is devoted to the development of an electromechanical system for a small-power wind power plant with a vertical rotor. An induction generator with a squirrel-cage rotor is used as the electromechanical converter of the developed system. The work proposes a system structure, defines approaches for induction generator control, and develops an algorithm for finding the optimal operating mode. To verify the correctness of the proposed solutions, a mathematical model of the system has been developed and studies have been conducted that have confirmed that the developed system maximizes the generated power at different wind speeds. The results obtained may be useful for manufacturers of wind power plants, which will contribute to their distribution and further development of small-scale generation in the country.

Keywords: wind power plants; vertical rotor; squirrel-cage induction generator; IFOC ; MPPT.

1. Introduction

Today, one of the most important areas of renewable energy is the development of wind energy systems [1,2]. In the context of the growing need for energy independence and the transition to renewable energy sources, wind energy occupies one of the key places. The highest efficiency coefficient is achieved by wind energy installations with a horizontal axis of wind energy converters, but for their effective operation, a sufficiently high and constant wind speed is usually required. Such installations are characterized by high installed power and significant capital costs are required for their installation. In Ukraine, high average wind speed is only in certain regions, so the use of small-capacity wind energy installations with a vertical axis is of particular relevance. Such installations are able to provide fully or partially autonomous power supply for private and commercial facilities. However, the efficiency of such installations directly depends on their electromechanical system and the ability to adapt to unstable wind conditions. The use of induction electric machines in wind power plants with a vertical axis of rotor rotation is one of the promising areas of development of small and medium-sized distributed power systems. The simplicity of design, mechanical reliability and relatively low cost of induction machines make them an attractive alternative to permanent magnet synchronous generators, especially for autonomous and weak power systems. To ensure effective conversion of wind energy in conditions of changing its strength, such electromechanical systems must be fully controlled, which is achieved by using semiconductor energy converters and appropriate control algorithms. This work is devoted to the development of control algorithms and the study of the electromechanical system operation that will provide the maximum level of electrical energy generation at different wind speeds.

2. Object and subject of research

The object of research is the process of converting wind energy into electrical energy, which occurs in wind power plants with a vertically positioned rotor and an electromechanical system with fully controlled induction electric machines.

The subject of the research is approaches and algorithms for controlling electromechanical systems with induction electric machines as part of wind power plants with a vertically positioned rotor, which should ensure the generation of maximum electrical energy when the wind speed changes.

3. Target of research

The purpose of the research is to determine approaches and develop algorithms for controlling an electromechanical system with an induction electric machine of a wind power plant, which will ensure the maximization of generated electricity when the wind speed changes.

To achieve this purpose, the following tasks should be solved:

– determining the structure of the electromechanical system of a wind power plant;

– synthesis of an induction electric machine control algorithm;

– development of an algorithm for finding the optimal operating point based on the criterion of maximum generated power;

– development of a mathematical model and research conduction of the wind power plant electromechanical system operation.

4. Literature analysis

There is a large number of works that is devoted to the development of wind power systems. In works [3-5], the main attention is paid to the aerodynamics of Darrieus and Savonius rotors. These works propose and justify changes in the geometry of rotors that will contribute to increasing the efficiency of wind energy conversion and improving their self-starting capabilities. Increasing the efficiency of wind energy converters allows to improve the operation of any wind power system, regardless of the type of electromechanical converter or types of control algorithms.

A lot of attention is paid to the use of induction double-fed electric machines as an electromechanical converter for wind power systems [6-10]. The advantage of such systems is that the electric converter is connected to the rotor circuit, and accordingly its power can be significantly reduced compared to the power of the electromechanical converter itself. But this advantage is achievable only under the condition of an almost constant value of wind energy, and in case of wind force changes, it is necessary to ensure a change in the geometry of the rotor blades, which significantly affects the cost of the system and its complexity. Therefore, induction machines with dual power supply are used mainly in powerful wind energy systems with horizontal rotor placement.

Another important direction of development of wind power systems, for which a large number of works [11-13] is devoted, is the use of synchronous generators with permanent magnets as an electromechanical converter in such systems. Compared with induction generators with a squirrel-cage rotor, such electric machines have a slightly higher efficiency, better weight-and-dimensions and their control is somewhat simpler. However, the cost of synchronous generators with permanent magnets is higher, which leads to an increase in the cost of the entire system.

5. Research methods

For solving the defined tasks, the principles of the electric machines theory, the electric drives theory, the automatic control theory, and methods of mathematical modeling were used.

6. Research results

6.1. Structure of a wind power system

Wind power plants with a vertical rotor of small and medium power can be used for full or partial power supply of private houses, small enterprises and other facilities. The distribution of such systems allows to reduce the load on electrical networks and to provide power to autonomous facilities. The structure of such systems when using induction electric machines is shown in Fig. 1.

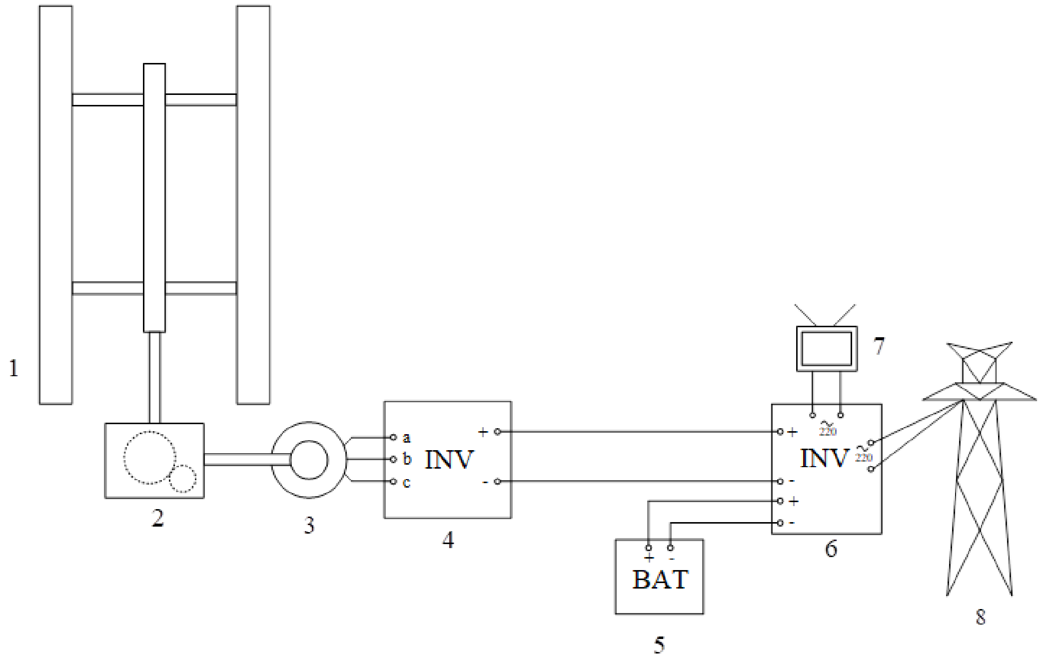

Figure 1. Structure of a wind power system:
1 – H-type vertical wind turbine; 2 – gearbox; 3 – induction generator; 4 – inverter;
5 – rechargeable battery; 6 – hybrid grid inverter; 7 – load; 8 – electrical grid.

The general principle of operation of such system is as follows: a wind turbine (1) converts wind energy into the energy of rotating mechanical motion, which is transmitted to the shaft of an induction generator (3) through a gearbox (2); electromechanical system consisting of induction generator (3) and inverter (with a built-in DC link) (4) converts the energy of mechanical motion into DC electrical energy; a hybrid grid inverter (6) performs the functions of controlling the charge/discharge of the battery (5), transferring energy to the grid (8) and to the load (7).

Thus, the above structure of the wind power system allows for the distribution of control functions: the hybrid grid inverter provides control of the energy transfer processes between the DC link, the battery, the load and the grid, and the induction generator inverter provides the selection of the operating mode of the wind power plant, which allows maximizing the amount of generated energy.

A vertical rotor wind turbine generates mechanical power, which is determined by the formula:

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot C_p(\lambda), \quad (1)$$

where: P – power generated by a turbine;

$C_p(\lambda)$ – wind energy utilization coefficient (is a function of quickness λ);

ρ – air density;

A – turbine rotor area (defined as the product of the turbine length and diameter $A = D \cdot L$);

v – wind speed;

λ – quickness is determined by the formula:

$$\lambda = \frac{\omega \cdot R}{v}, \tag{2}$$

where ω is rotor angular speed;

R –radius of the turbine.

From formula (1) it is seen that the generated power is proportional to the third power of the wind speed, and depends on the wind energy utilization coefficient $C_p(\lambda)$, which, in turn, is a nonlinear function, which is determined empirically for a specific type and size of the wind rotor. But it is characteristic of any rotor that the function $C_p(\lambda)$ has a clearly defined maximum. Therefore, to ensure optimal operation of a wind turbine, it is necessary to change the rotor speed when the wind speed changes. This can be achieved by using an electromechanical speed control system while simultaneously searching for the optimal operating point.

The structure of the electromechanical system of a wind power plant is shown in Fig. 2.

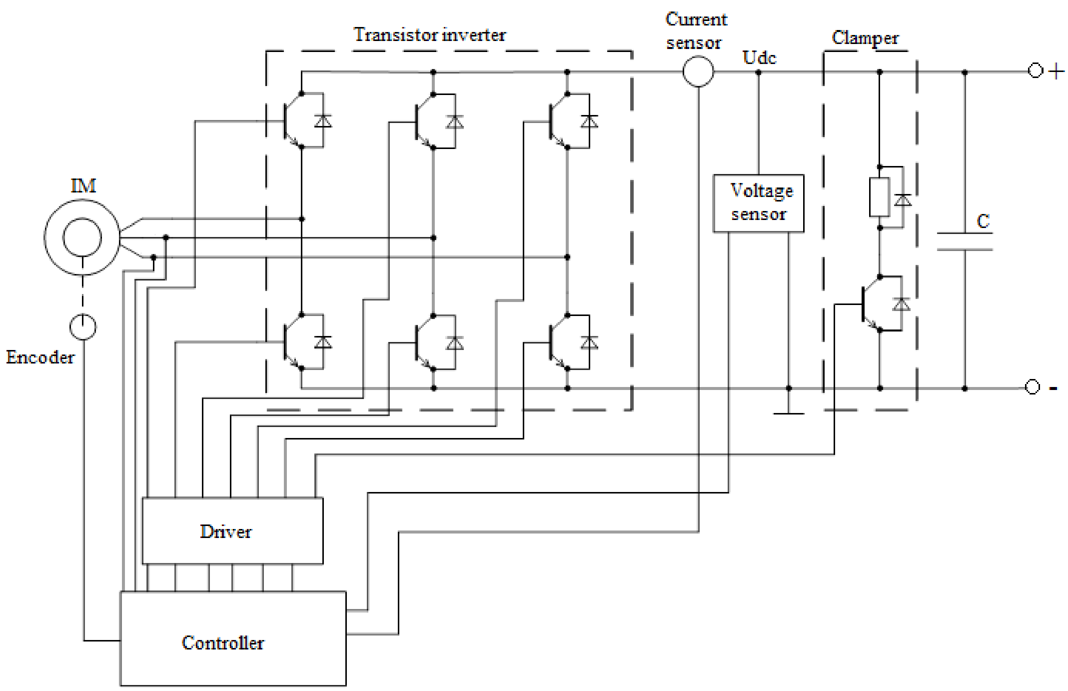

Figure 2. Structure of the wind power plant electromechanical system.

In addition to the induction machine and the inverter itself, the electromechanical system includes a set of auxiliary devices, namely: a driver and a controller for direct control of the inverter, speed, current and voltage sensors, a DC link capacitance and a clamper for implementing of protection functions. Considering that stabilizing voltage in the DC link is provided by the hybrid inverter, the main function of the electromechanical system is to regulate the rotation speed at which the maximum generated power is achieved. Moreover, to determine the current generation level, it is enough to measure the current at the inverter output, since exactly value of the current will determine the amount of generated power. Thus, in the inverter controller it must be implemented an algorithm for controlling the speed of the induction generator and an algorithm for finding operation mode with maximum generated power.

Hybrid grid inverters are devices that are currently being produced by the industry, for example Daxtromn HGP-5500W or other. Such inverter, maintaining a constant voltage level in the DC link, controls energy transfer, namely:

– at a high level of generation and low load, the battery is charged and after charging, the energy is transferred to the network;

– when the load is greater than generation, energy is consumed from the network (if available) or from the battery.

6.2. Algorithm of induction generator control

To regulate the rotation speed of the rotor shaft, it was decided to use indirect field-oriented control [14]. This control method allows ensuring high dynamics of speed change and maintaining it at a given level with high accuracy.

The chosen method allows independent control of the magnetic flux and electromagnetic torque of an electric machine, which is similar to the control of a DC motor with independent excitation. This is achieved due to the fact that control is carried out through two current components: flux and torque. Moreover, the possibility of independent torque control through the current torque component is achieved only with a constant magnetic flux, i.e. the change in flux and torque must be carried out not simultaneously.

The synthesis of the control algorithm is carried out on the basis of a two-phase model of induction machine in a rotating coordinate system d-q. The system of equations describing this model has the following form (3). It includes equations for determining the angular acceleration (mechanical component), electromagnetic torque, and derivatives of the stator current components along the axes d and q, the derivatives of the rotor flux linkage components along the axes d and q, the angular rotation frequency of the stator field vector and the rotor flux linkage module:

$$\begin{aligned}
&\dot{\omega} = J^{-1}(M - M_c) \\
&M = \mu_1(\psi_{2d} i_{1q} - \psi_{2q} i_{1d}) \\
&\dot{i}_{1d} = -\gamma i_{1d} + \omega_0 i_{1q} + \alpha\beta\psi_{2d} + \beta p_n \omega \psi_{2q} + \frac{1}{\sigma} u_{1d} \\
&\dot{i}_{1b} = -\gamma i_{1q} - \omega_0 i_{1d} + \alpha\beta\psi_{2q} - \beta p_n \omega \psi_{2d} + \frac{1}{\sigma} u_{1q} \\
&\dot{\psi}_{2d} = -\alpha\psi_{2d} + p_n \omega \psi_{2q} + \alpha L_m i_{1d} \\
&\dot{\psi}_{2q} = -\alpha\psi_{2q} - p_n \omega \psi_{2d} + \alpha L_m i_{1q} \\
&\dot{\varepsilon}_0 = \omega_0 = \omega p_n + \omega_2 = \omega p_n + \alpha L_m (i_{1q} / |\psi|) \\
&|\psi| = \sqrt{\psi_{2d}^2 + \psi_{2q}^2}
\end{aligned}, \qquad (3)$$

where: ω – angular frequency of rotation of the rotor;

J – inertia moment of the rotor;

M – electromagnetic torque;

M_c – load torque;

i_{1d}, i_{1q} – components of the stator current d and q;

ψ_{2d}, ψ_{2q} – components of the rotor flux linkage d and q;

u_{1d}, u_{1q} – stator voltage components d and q;

p_n – number of pole pairs;

ω_0 – angular rotation frequency of the stator field vector;

ω_2 – angular rotation frequency of the rotor field vector;

ε_0 – position of the stator magnetic field vector;

L_m – inductance of the magnetization circuit;

σ, α, β, γ, μ_1 – positive constants, which are defined as follows:

$$\sigma = L_1\left(1-\frac{L_m^2}{L_1L_2}\right), \beta = \frac{L_m}{\sigma L_2}, \mu_1 = \frac{3}{2}p_n\frac{L_m}{L_2},\ \alpha = \frac{R_2}{L_2}, \gamma = \frac{R_1}{\sigma} + \alpha L_m\beta, \tag{4}$$

where: L_1, L_2 – stator and rotor inductances;

R_1, R_2 – active resistances of stator and rotor.

Based on the condition of zero error in the flux regulation of an induction generator in steady-state modes, using the fifth and sixth equations from system (3), it is possible to formulate an expression for determining the set value of the stator current flux component:

$$i_{1d}^* = \frac{\alpha\psi^* + \dot{\psi}^*}{\alpha L_m}, \tag{5}$$

where ψ^* – set value of the rotor flux linkage.

Speed regulation is carried out by torque regulation, which requires regulation of the current torque component at a constant flux linkage value. The simplest typical regulator that provides a zero value of static error is a PI regulator. We will use this type of regulator to form the torque component of the current set value:

$$\begin{aligned} i_{1q}^* &= \frac{1}{\mu\psi^*}(-k_\omega\tilde{\omega} + \hat{M}_c) \\ \dot{\hat{M}}_c &= -k_{\omega i}\tilde{\omega} \end{aligned}, \tag{6}$$

where: $\tilde{\omega} = \omega - \omega^*$ – error of rotation speed regulation;

$\hat{M}_c$ – estimated value of unknown constant load torque;

$(k_\omega, k_{\omega i}) > 0$ – coefficients of the proportional and integral parts of the PI speed controller.

It is also advisable to use PI controllers to form the flux and torque components of currents. The expressions for determining the control actions (v_d, v_q) for regulating the current components have the following form:

$$\begin{aligned} v_d &= -k_{id1}\tilde{i}_{1d} + x_d \\ \dot{x}_d &= -k_{ii}\tilde{i}_{1d} \end{aligned}, \tag{7}$$

$$\begin{aligned} v_q &= -k_{iq1}\tilde{i}_{1q} + x_q \\ \dot{x}_q &= -k_{ii}\tilde{i}_{1q} \end{aligned}, \tag{8}$$

where: $\tilde{i}_{1d} = i_{1d} - i_{1d}^*$ – error of d-axis current component;

$\tilde{i}_{1q} = i_{1q} - i_{1q}^*$ – error of q-axis current component;

x_d, x_q – integral components of current regulators;

$(k_{id1}, k_{iq1}, k_{ii}) > 0$ – coefficients of the proportional and integral components of the regulator.

6.3. Algorithm for searching the optimal operating point using the criterion of maximum generated power

This algorithm is similar to various MPPT (Maximum Power Point Tracking) algorithms [15,16], which are designed to select the operating point of the system at which the maximum generated power is achieved. Such algorithms are often used in solar power plants and in some cases can be embedded in specialized equipment for such systems.

To implement such an algorithm for the considered wind power plant, it is advisable to use the Perturb and Observe principle (P&O). This principle is iterative and is widely used due to its efficiency and low computational complexity. The essence of P&O work is to periodically introduce a small perturbation (Δ) into the control parameter of the system (the set value of generator rotation speed) and analyze the change in the output power of the wind power plant (in the proposed system, instead of measuring the power, it is enough to determine the value of the inverter output current). A distinctive feature of such an algorithm from existing ones in solar power plants is that in wind power plants the response to the perturbation can be assessed only after the completion of the transient process, which can be quite long due to the significant inertia of the wind turbine.

The algorithm includes the following steps:

1. Initialization. The initial value of the rotation frequency ω is set and after the steady-state operation mode is reached, the initial power P_a is measured (inverter output current I_{out}). The previous values of frequency and power are assumed to be zero.
2. Perturbation. The rotation frequency set value changes by the value $\Delta\omega$.
3. Waiting. The transition process must complete before taking further steps.
4. Вимірювання. Після внесення збурення та після завершення перехідного процесу вимірюється нове значення потужності.
5. Analysis and decision-making:
   a. Determination of power increase $\Delta P_a = P_a(n+1) - P_a(n)$.
   b. If $\Delta P_a>0$: sign of $\Delta\omega$ is preserved.
   c. If $\Delta P_a<0$: sign of $\Delta\omega$ changes to the opposite.
   d. If $\Delta P_a=0$: sign of $\Delta\omega$ is preserved.
6. Update. Saving of the current frequency and power values as previous values and return to step 2.

The key parameters of the algorithm are:

- The perturbation step size $\Delta\omega$. This parameter is responsible for the time needed to reach the maximum power point and the magnitude of the oscillations around it. Smaller step values provide a more accurate approximation in steady state, but slow down the system's response to changes in wind speed.
- MPPT period is the waiting step time. The time interval between successive disturbances should be long enough for the system to react and the transient process to complete. At the same time, this period should not be too long so as not to lose the efficiency of reaching the optimal mode with frequent changes in wind speed.

6.4. Study of the wind power plant electromechanical system operation

The study the operation of the proposed system and the developed control algorithms should be performed through mathematical modeling in the MATLAB Simulink environment. The system under study includes: a wind turbine with a Darrieus H-type rotor with a diameter of 2.4 m and 3 blades with a length of 3.6 m; an induction electric machine AIR132M8, which is connected to the turbine shaft through a gearbox with a gear ratio of 2; a device for controlling the flux and rotation speed of the induction machine and a device for determining the optimal operating point. The inverters included in the system are considered idealized, that is, those that form currents and voltages instantly and without distortion. The model of the system under study consists of the following subsystems:

1. The subsystem that models the operation of a wind turbine is built on the basis of equations (1)-(2). In addition, this subsystem implements the dependence $C_p(\lambda)$ in the form:

$$C_p(\lambda) = c_1(\frac{c_2}{\lambda} - c_3)e^{-\frac{c_4}{\lambda}} + c_5\lambda\,, \quad (9)$$

where $c_1 \ldots c_5$ – coefficients that are characteristic of a particular wind turbine (during calculations these coefficients had the following values: $c_1=0.5176$, $c_2=116$, $c_3=5$, $c_4=21$, $c_5=0.0068$).

The calculation of the torque created by the turbine is performed using the formula:

$$M = \frac{P}{\omega_в}\,. \quad (10)$$

For the specified turbine parameters, the dependence of the maximum power generated by the turbine depending on the wind speed is shown in Fig. 3.

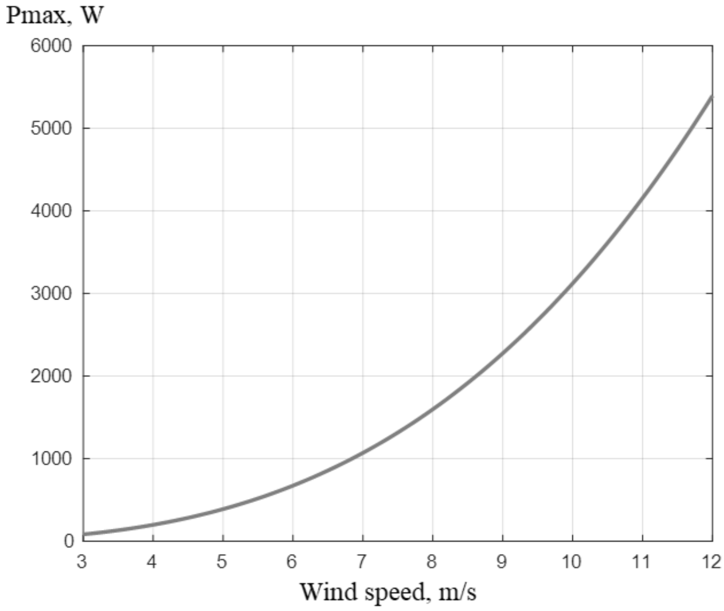

Figure 3. Dependence of the maximum power generated by a wind turbine on wind speed.

2. The subsystem that models the operation of an induction generator is built on the basis of the equations system of (3).

3. The subsystem that models the flux and rotation speed control device is built based on equations (5)-(8).

4. The subsystem that models the operation of the algorithm for finding the optimal operating point is implemented according to the material from subsection 6.3.

To verify the properties of the system, its operation was simulated when the wind speed changes according to graph a) in Fig. 4. The set value of the flux coupling is shown in graph b) in Fig. 4.

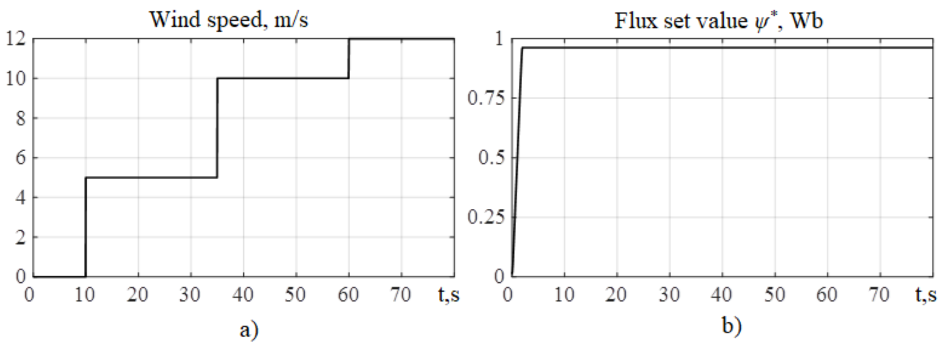

Figure 4. Wind speed graphs and set value of flux coupling.

As can be seen from the graphs above, the flux coupling set value is changed from 0 to 2 s, and after that it remains unchanged, which is necessary for the correct operation of the selected control algorithm.

The algorithm for finding the optimal operating point is activated at time 3 s. From this moment on, the speed set value begin to change. The graph of the speed setting change is shown in Fig. 5.

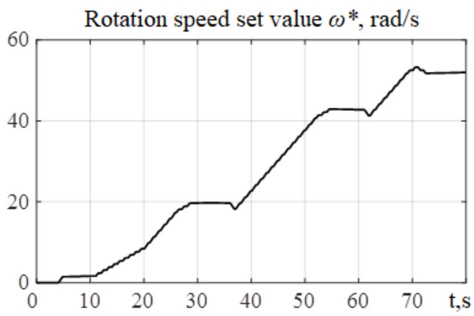

Figure 5. Graph of the rotation speed set value.

The frequency change is carried out stepwise with a discreteness of 1 s, which is due to the settings of the search algorithm. This leads to the appearance of transient processes at each point of updating the frequency setting, which in turn leads to errors in the speed control and pulsations of the electromagnetic torque. The graphs of the corresponding values are shown in Fig. 6.

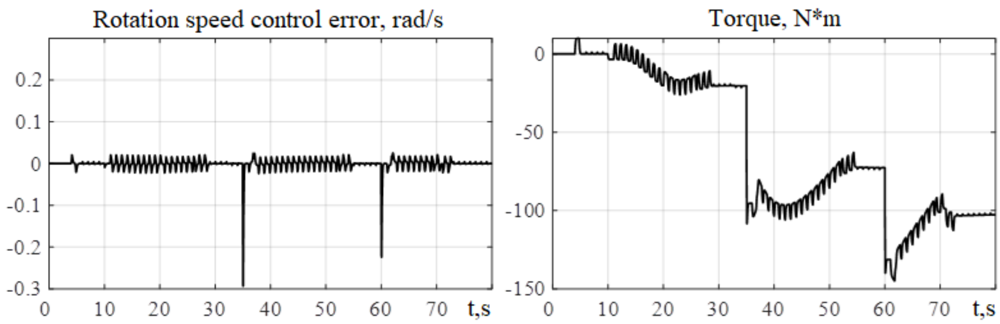

Figure 6. Graphs of error in rotation speed and motor torque regulation.

The negative value of the torque is due to the generator operation mode of the electric machine.

The presence of torque and rotation speed pulsations leads to the appearance of pulsations of mechanical power on the generator shaft and electrical power at the inverter output. The graphs of mechanical and electrical power are shown in Fig. 7.

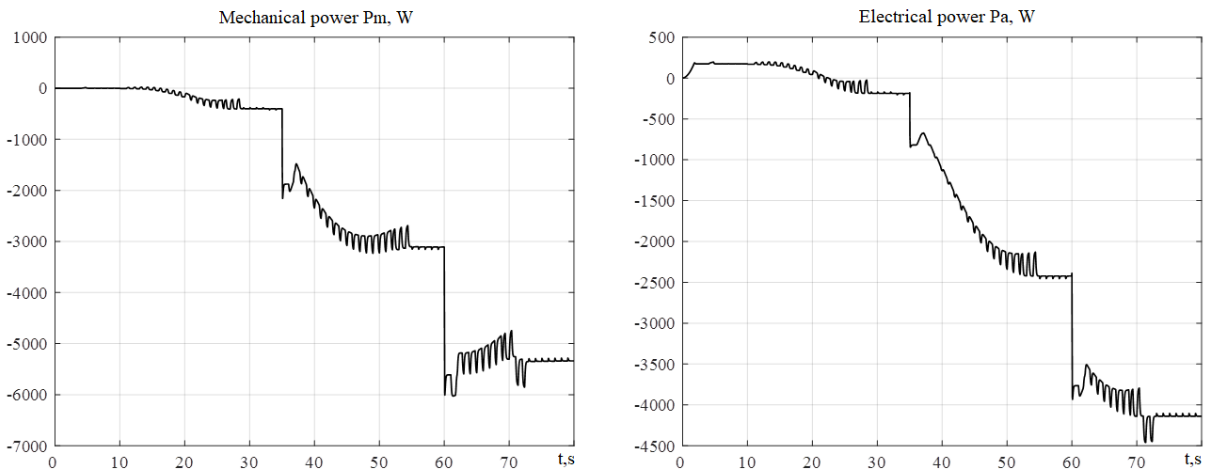

Figure 7. Graphs of mechanical and electrical power.

As can be seen from the graphs above, each time after a change in wind speed, the process of reaching a new point of maximum generated power begins, the duration of this processes depends on the magnitude of change in wind speed. Comparing the results obtained with the results shown in Fig. 3. it can be seen that the proposed control approach provides a gradual system entry into the mode that corresponds to the optimal one in criterion of maximum generated power: for a wind speed of 5 m/s – 400 W, 10 m/s – 3100 W, 12 m/s – 5300 W of mechanical power. The electrical power is less than the mechanical power, which is due to energy losses in the induction generator.

It should be noted that at zero wind speed, the use of the proposed control approach leads to the fact that the induction machine will operate not in generator mode, but in motor mode, consuming energy from the grid or battery. Therefore, at low wind speed, it is advisable to stop the wind turbine and turn off the inverter.

7. Prospects for further research development

Further development of the proposed system research should be carried out in two directions: examination of the influence of the non-ideal inverters operation, since the features of their construction will affect the efficiency of the system; reduction the process time of finding a new operating point when the wind speed changes, which will also ensure an increase in the efficiency of the system, especially in gusty winds.

8. Conclusions

The paper proposes a structure of electromechanical system for a small-power wind power plant, which includes a wind turbine, a gearbox, a squirrel-cage induction generator, a three-phase inverter, and a hybrid grid inverter.

To control the system, it is proposed to use the indirect field-oriented control method and the algorithm for finding the optimal operating point to ensure energy generation at the maximum level is developed.

To verify the correctness of the proposed approaches and developed algorithms in the MATLAB Simulink environment the model of the system was created and studies of its operation were conducted. Obtained results confirmed that in the developed system, when the wind speed changes, a transition is made to a mode that is optimal according to the criterion of maximum generated power.

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