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INVESTIGATION OF ENERGY EFFICIENCY OF WATER SUPPLY SYSTEM WHEN POWERED BY AN ALTERNATIVE ENERGY SOURCE

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The nature of the efficiency change in pump systems powered by an alternative source of electricity in conditions of a given pressure stabilization is investigated. An electromechanical water supply system powered by an alternative energy source using a static compensator (STATCOM) is considered. The observer of energy efficiency of the pump installation based on theory of artificial neural networks, which training occurs on the basis of static characteristics of the unit, is constructed. The results and analysis of investigations of the efficiency level changes during a typical daily cycle of water consumption are shown. References 12, figure 5.

Key words: pump unit; efficiency; pressure stabilization; voltage regulation; induction generator.

Introduction. The transition to alternative energy sources allows to obtain electricity economically and environmentally, which is relevant against the background of rising trends in energy prices used in electricity generation. In some areas, it is possible to use only autonomous power generation systems, as laying the power grid is unprofitable and impractical. Such systems are usually performed by combining an electric generator and a drive motor: an internal combustion engine or a wind or hydro turbine.

Control of water supply systems powered by alternative energy sources, such as wind turbines, is carried out using both systems with synchronous and inductions wind turbines [1].

Among modern alternative systems of electricity generation, wind turbines based on induction generators with self-excitation (SEIG) are becoming more common. Stabilization of the SEIG voltage avoids overturning the generator at high load on it. The issue of voltage stabilization is relevant and can be solved in many ways. The most widespread are systems with output regulation using a static compensator (STATCOM) [2] and with an electronic load regulator (ELC) [3].

The process of determining and monitoring the main technological parameters of turbomechanisms is an integral part of their control system. However, the sensors required to transmit information to the system are expensive or difficult to install due to the inherent design of the hydraulic system. Parameters such as pump efficiency cannot be measured directly, only indirect way can be determined using a number of sensors, which increases the cost of the system.

One of the perspective ways to determine the energy efficiency of turbomechanism systems is the use of efficiency observers. Observers are designed on the basis of artificial neural networks, which based on already known measured coordinates, such as pressure and pump performance, allow to estimate the values of other coordinates [4], [5].

On the other hand, the issue of stability of water supply systems is important. The most common solution to this problem is to ensure the stabilization of pressure in the hydraulic network by regulating productivity depending on changes in hydraulic resistance, which is necessary to meet both technological and social requirements.

The aim of the paper is to investigate the energy efficiency of a pump unit powered by an induction generator with regulated voltage, in conditions of stabilization of a hydraulic network pressure given level using the theory of artificial neural networks.

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Materials and results of the research. The research was carried out on the basis of a water supply system powered by a wind turbine when regulating the voltage of the induction generators (IG), in conditions of stabilization of the hydraulic network pressure. The functional diagram of the control system is shown in Fig. 1.

In Fig. 1 the following notations are entered: IG – induction generator; STATCOM – static compensator; FC – frequency converter; IM – induction motor; P – pump unit; NN – pump efficiency observer based on neural network; u_1^*, u_2^* – voltage and pressure references, respectively; *PU, PH* – voltage and pressure controllers set to PI laws, respectively; $K_{ззU}$, $K_{ззH}$ – voltage and pressure feedback coefficients, respectively; ω_1 – IG rotor angular speed; ω – pump velocity; T_L – load torque on the shaft; Q – pump productivity; H – pump pressure; $\hat{\eta}$ – estimated value of the pump efficiency; ω^* – speed reference; U_a, U_b, U_c – stator phase voltage; U_{abc} – given stator phase voltage.

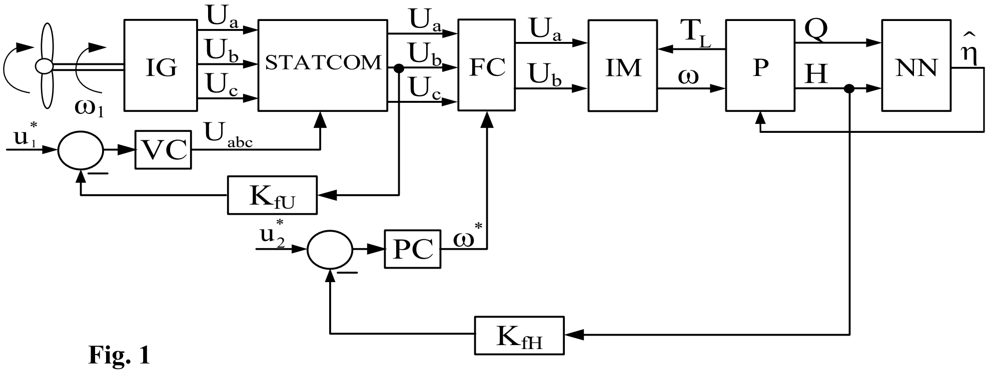

Fig. 1

The investigated system is made with two frequency converters, which makes it possible to place the wind turbine and pump separately from each other to increase the efficiency of the system in selecting the optimal areas for objects [6]. It also allows to introduce an additional source of energy from other types of alternative sources, such as solar energy, which do not require additional control [7].

The induction generator is rotated by a turbine whose velocity is maintained constant. A parallel battery of capacitors connected in a triangle is used for self-excitation of the IG. Capacitor battery, which is part of the static compensator, in such systems is calculated so that the SEIG is self-excited at rated load.

The key control signals of the STATCOM inverter come from the PWM controller, which, depending on the voltage received from the voltage regulator, gives a signal to close these keys. The task of the voltage regulator is to maintain a constant voltage of the SEIG, which in turn makes constant the value of the generated voltage.

The mathematical model of an induction generator in an arbitrary coordinate system is described by the following system of nonlinear differential equations [8]:

$$\begin{aligned} \frac{d\Psi_S}{dt} &= U_S - R_S i_S - \omega_e J \Psi_S, \\ \frac{d\Psi_R}{dt} &= -R_R i_R + (p_n \omega_1 - \omega_e) J \Psi_R, \end{aligned} \tag{1}$$

where $J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$, $\Psi_S = \begin{bmatrix} \Psi_{Sd} & \Psi_{Sq} \end{bmatrix}^T$, $\Psi_R = \begin{bmatrix} \Psi_{Rd} & \Psi_{Rq} \end{bmatrix}^T$ are the stator and rotor flux linkage vectors; $i_S = \begin{bmatrix} i_{Sd} & i_{Sq} \end{bmatrix}^T$, $i_R = \begin{bmatrix} i_{Rd} & i_{Rq} \end{bmatrix}^T$ are the vectors of stator and rotor currents; $U_S = \begin{bmatrix} U_{Sd} & U_{Sq} \end{bmatrix}^T$ is the stator voltage vector; R_S and R_R are the active stator and rotor resistance; p_n is the number of pole pairs; ω_e is the angular velocity of rotation of an arbitrary coordinate system *d-q*.

Excitation capacitors with capacitance C are connected in parallel to the stator windings and in parallel to them – the load due to the hydraulic resistance change of the network in accordance with the daily cycle of water consumption by housing and communal services.

Then, the equation for the voltage on the stator windings (on the excitation capacitors) is obtained on the basis of Kirchhoff's first law in the form:

$$-C\frac{dU_S}{dt} = i_S + i_L\,, \tag{2}$$

where $i_L = \begin{bmatrix} i_{LA} & i_{LB} \end{bmatrix}^T$ is the load current vector.

The classical model of an induction motor in the coordinates of the stator *a-b* [8] is used. The frequency converter implements the quadratic law of frequency control $U/f^2 = const$ [9]. The pressure regulator is set to the PI control law [10] and provides stabilization of the network pressure at a given level.

The pump unit is described by the first-order differential equation (3), the equation for determining the pressure (4), the equation for determining the loading torque when observing the pump efficiency (5) [11]:

$$\chi dQ/dt = H_{0n}\omega^2/\omega_n^2 - H_{st} - (a_n + a)Q^2, \tag{3}$$

$$H = H_{0n}\omega^2/\chi\omega_n^2 - a_nQ^2, \tag{4}$$

$$T_L = \rho gQH/\hat{\eta}\omega, \tag{5}$$

where χ is the integration time constant of the pump; H_{0n} is the nominal pressure at zero feed at nominal speed; ω_n is the nominal speed of pump; H_{st} is the geodetic height of water level; a_n is the nominal hydroresistance of the pump; a is the hydraulic resistance of the network; ρ is the water density; g is the free fall acceleration; t is the time.

While working with neural networks, their mathematical description is important. In the general case, the equation of neurons is described by the following expression [4]:

$$y_i = \lambda_i\Big(\sum_{j=1}^{m} x_j w_{ij} + b_i\Big), \tag{6}$$

where $x_1, x_2, \ldots x_m$ are the inputs of the neuron; $w_{i1}, w_{i2}, \ldots, w_{im}$ are the weight coefficients of synaptic bonds; b_i is the displacement of the neuron; $\lambda_i(.)$ is the activation function of the neuron.

Equations describing each neuron in the case of a two-layer neural network with 10 neurons in the first layer are written as follows:

$$\begin{aligned} &y_1 = th((Hw_{11} + \omega w_{12} + b_1)/a_1) \\ &y_2 = th((Hw_{21} + \omega w_{22} + b_2)/a_2) \\ &\ldots \\ &y_{10} = th((Hw_{101} + \omega w_{102} + b_{10})/a_{10}) \end{aligned}\,, \tag{7}$$

where H, ω are the neuron inputs; a_1 is the coefficient of inclination of the function of the tangential hyperbolic tangent tansig.

Therefore, the general equation that determines the operation of an artificial neural network to estimate the efficiency of the pump is written as follows:

$$\begin{aligned} \hat{\eta} = c(&th((Hw_{11} + \omega w_{12} + b_1)/a_1)w_1 + th((Hw_{21} + \omega w_{22} + b_2)/a_2)w_2 + \\ &+ th((Hw_{31} + \omega w_{32} + b_3)/a_3)w_3 + th((Hw_{41} + \omega w_{42} + b_4)/a_4)w_4 + \\ &+ th((Hw_{51} + \omega w_{52} + b_5)/a_5)w_5 + th((Hw_{61} + \omega w_{62} + b_6)/a_6)w_6 + \\ &+ th((Hw_{71} + \omega w_{72} + b_7)/a_7)w_7 + th((Hw_{81} + \omega w_{82} + b_8)/a_8)w_8 + \\ &+ th((Hw_{91} + \omega w_{92} + b_9)/a_9)w_9 + th((Hw_{101} + \omega w_{102} + b_{10})/a_{10})w_{10} + b). \end{aligned}\,, \tag{8}$$

where c is the slope factor of linear activation function.

Based on the given mathematical description of the electromechanical system elements, a model was obtained within the application packages MATLAB SimPowerSystems and Simulink to investigate the energy efficiency of the water supply system in terms of stabilization of pressure in the hydraulic system powered by wind turbine.

To measure the efficiency of the pump used an observer based on the neural network, which was designed in accordance with the method described in [12]. To create an artificial neural network to estimate the efficiency of the pump used a neural network editor (Network / Data / Manager) in the application package MATLAB. The training of the neural network was based on the catalog' characteristics of the pump and formed from 2 layers of 10 neurons in the first and 1 in the output layer. The training error was 0.031, the regression coefficient was 0.998, which indicates the profitability of the neural network and the possibility of using it as an observer of the efficiency of the selected pump.

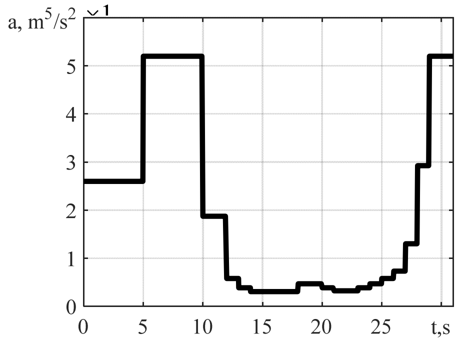

Fig. 2

During the research, the nature of the change the value of hydraulic resistance was adopted on the basis of one of the typical schedules of water consumption within the daily water supply cycle of residential buildings [10]. The graph of hydroresistance changes of the network is shown in Fig. 2. The daily cycle begins with 5 s, as it is necessary to first overclock the generator and induction motor.

The investigations were performed for the SEIG with a capacity of 5.5 kW, an induction motor – 4 kW and a pump – 3.7 kW for constant speed horizontal wind turbine. The pressure stabilization level is 48 m, which is the nominal pressure for the selected pump. The results of the study of the pump unit, generator and the level of pump unit efficiency are shown in Fig. 3-5 respectively, where U_g is line-to-line SEIG voltage; U_L is line-to-line load voltage.

From the graphs of the pump transients it is seen that when changing the hydraulic resistance, the pressure regulator works out the set value with a dynamic error of not more than 1%. The presence of the error of the set pressure is due to the stiff nature of the change in hydroresistance.

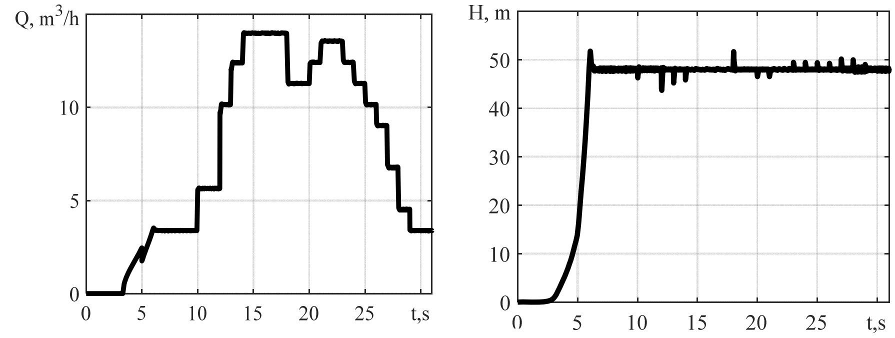

Fig. 3

The voltage controller stabilizes the value of the output line load voltage at 510 V. This confirms the fact that the proposed system maintains the value of the output voltage of the generator at a constant level regardless of the hydraulic resistance of the water supply system.

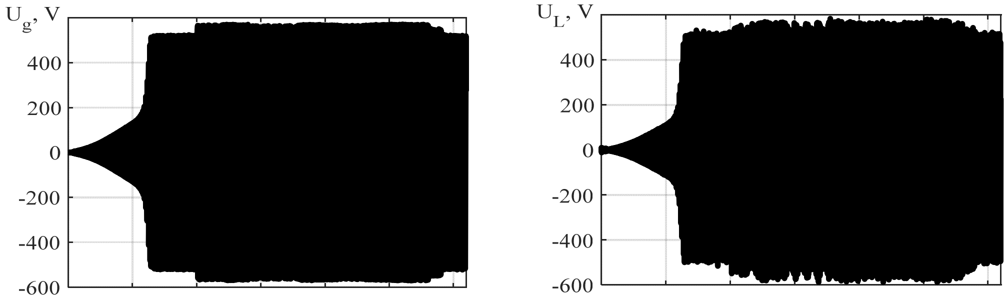

Fig. 4

The energy efficiency of the pump varies according to the change in hydraulic resistance. In the busiest periods of time the efficiency of the pump is 59%, which corresponds to the nominal value of the efficiency when operating at a pressure level of 48 m.

Conclusions. Investigations have shown that the developed control system allows to observe the energy efficiency of the pumping unit, which powered by an alternative source of electrical energy, in terms of pressure stabilization, with high accuracy. The pump efficiency reaches the maximum value at the nominal mode of pump and the drive motor operations. The dynamic error of the hydraulic network pressure at a given level when changing its resistance does not exceed 1%, which is admissible for technological and housing and communal requirements. The model developed in MATLAB allows to analyze the energy efficiency of the sensorless control system of the turbomechanism when controlling the magnitude and frequency of the voltage of the generator that supplies it. Given the analysis of research, it is recommended to use the results obtained both in the design of new and in the reconstruction of existing control systems of pumping units powered by a wind turbine with a self-excitated induction generator.

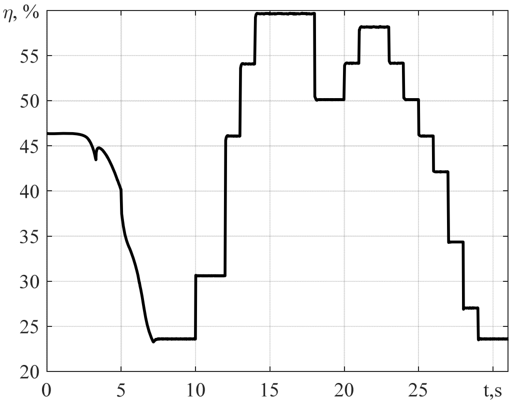

Fig. 5

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ДОСЛІДЖЕННЯ ЕНЕРГОЕФЕКТИВНОСТІ СИСТЕМИ ВОДОПОСТАЧАННЯ У РАЗІ ЖИВЛЕННЯ ВІД АЛЬТЕРНАТИВНОГО ДЖЕРЕЛА ЕНЕРГІЇ

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Досліджено характер зміни коефіцієнту корисної дії (ККД) в насосних системах у разі живлення від альтернативного джерела електричної енергії в умовах стабілізації заданого тиску. Розглянуто електромеханічну систему водопостачання, що живиться від альтернативного джерела електричної енергії через використання статичного компенсатора (STATCOM). Побудовано оцінювач енергоефективності насосної установки на основі теорії штучних нейронних мереж, тренування якої відбувається на базі статичних характеристик агрегату. Показано результати та аналіз досліджень зміни рівня ККД протягом типового добового циклу споживання води. Бібл. 12, рис. 5.

Ключові слова: насосна установка, ефективність, стабілізація тиску, регулювання напруги, асинхронний генератор.

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