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THE RESEARCH OF EFFICIENCY OF THE USE OF NEUROPREDICTOR IN THE CONTROL SYSTEM OF WATER-SUPPLY PUMP ELECTRIC DRIVE

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ДОСЛІДЖЕННЯ ЕФЕКТИВНОСТІ ЗАСТОСУВАННЯ НЕЙРОПРЕДИКТОРА В СИСТЕМІ КЕРУВАННЯ ЕЛЕКТРОПРИВОДОМ НАСОСУ СИСТЕМИ ВОДОПОСТАЧАННЯ

Purpose. To substantiate the application of the artificial neural network predictors in the water-supply pump control systems for forecasting the water consumption within 24 hours.

Methodology. The data for synthesis of an artificial neural network predictor have been obtained by experimental research studies on the operating water supply system. The mathematical model of the electric drive system of a pump has been created by using the object-oriented method. This model takes into consideration the nonlinearity of magnetic core characteristics of an induction motor and existence of the hydraulic network with distributed parameters at the pump exit. Using computer simulation, the following aspects were researched: the frequency regulation mode of asynchronous drive of a pump, dynamic ratings of pump drive for predicted value of water consumption and quality performance of pressure regulation.

Findings. On the base of experimentally obtained data the artificial neural network predictor, which adequately forecasts the water consumption value within 24 hours, has been synthesized. The systems controlling an artificial neural network predictor pump have been synthesized; they realize different laws of the pump output pressure regulation. The laws of frequency control of water-supply pump electric drive system have been substantiated.

Originality. For the first time, it is proposed to use the artificial neural network predictor in the pump control system to forecast the value of water consumption and synthesis of the control influences on the pump electric drive with taking the water consumption into consideration. Results, which demonstrate the mutual influences of processes in the water-supply network and electromagnetic processes in the electric drive with induction motor, have been obtained.

Practical value. Due to consideration of the predicted value of water consumption in the offered pump control system, the efficacy of the water supply system has increased while the unproductive losses of water have decreased.

Keywords: *water-supply pump, artificial neural network predictor, asynchronous electric drive, mathematical modelling*

Introduction. One of priority problems of the most world countries in the 21st century is to supply quality drinking water to the population. The solution of this problem is necessary for maintaining health, improving life activity and increasing the living standard of population. At the same time, in our country's conditions finding the solution of this problem is considerably complicated because of the unsatisfactory technical state and wearing out of the water-supply and overflow-pipe systems, their high energy-intensity caused by applications of out-of-date technologies and equipment.

Maximal satisfaction of consumers' demands for the continuous water supply with required pressure with substantial wear of pipelines has resulted in the unproductive losses of water. In different regions these losses make from 15 to 37 %. In order to reduce water losses the enterprises apply the hourly schedule of water supply, as well as pressure decrease at the day and night time.

Analysis of the recent research. In order to increase energy efficiency, the frequency controlled electric drives are widely used in the water supply and overflow-

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pipe systems [1, 2]. Traditionally, such drives realize the scalar control law $U/f^2 = \text{const}$, since dynamics of electric drives does not influence substantially dynamics of the system, and provide regulation of pressure at the set point (often at a pump output). In order to increase power efficiency of such systems, the change of the control law and the additional control loops have been used for providing the pump operation with maximum possible coefficient of efficiency [3–5].

In the water supply system with the frequency-controlled electromechanical converter, it is possible to practically avoid emergency situations caused by water hammer effect, that appear while starting the system and changing working modes. However, there are still substantial losses of energy and water as a result of the static and dynamic pressure. As stated in [4] the highest level of energy and water saving in the water supply systems is achieved on condition of accordance of the supplied water amount to the used water amount. For this purpose it is necessary to include a device in the control system which will predict the water consumption at the next moment of time and will form the corresponding control action. For development of such devices, one can use the approaches based both on the fundamentals of statistical data analysis and on the methods of theory of intellectual control, in particular, artificial neural networks [6].

It is known, that daily schedules of the water consumption differ substantially depending on a season, temperature of surrounding air, a day of a week and other factors. Therefore, in the programmable control systems it is expedient to use the dynamic models of water consumption, which take into consideration changes of the above mentioned factors. Increase in prediction exactness for water consumption is also achieved by taking into consideration a prehistory, i.e. the amount of water used for previous hours [4].

Unsolved aspects of the problem. In order to improve the quality of water supply system operation and reduce water losses, exact prediction of the water consumption value is required depending on time of the day, season and seasonal factors.

To increase energy efficiency of the water supply system and reduce unproductive water losses, [7] proposes to include the artificial neural network predictor in the pressure stabilizing system (Fig. 1). The task of such a device is to correct the set value of pressure depending on water consumption. The structure of the proposed neuropredictor is given in Fig. 2.

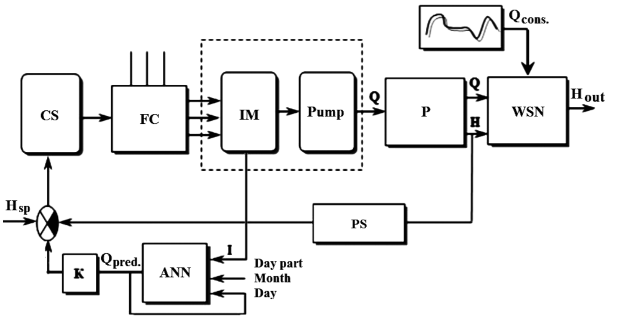


Fig. 1. The structural scheme of the control system with the neuropredictor:

CS – control system; FC – frequency converter; IM – induction motor; P – short pipeline; WSN – water supply network; PS – head (pressure) sensor; ANN – artificial neural network (neuropredictor)

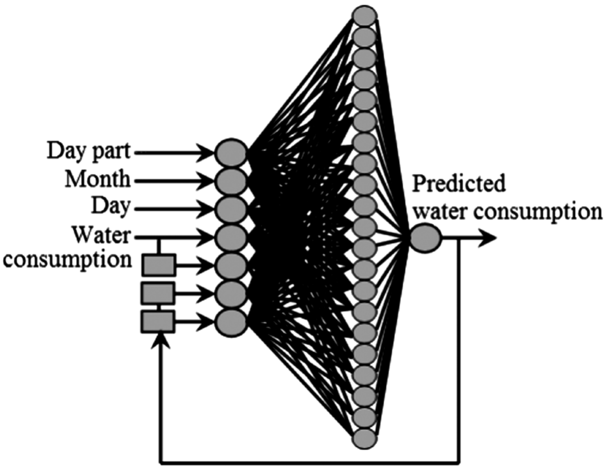


Fig. 2. The structure of neuropredictor based on recurrent artificial neural network with one hidden layer

The application of the artificial neural network predictor in the control system of a pump for forecasting the flow rate value gives an opportunity to synthesize the new control laws for a pump with the purpose of increasing resource saving and energy efficiency. The synthesis of these laws requires the analysis of working modes of the proposed system with taking into consideration the characteristics of the electric drive and the water supply network.

Objectives of the article. Tasks of the article are to research water supply system with the real character of water consumption using the mathematical modeling method of the working modes of pump in the and to validate a possibility of correcting control laws for a pump electric drive by taking into account the water flow-rate value, which is forecast with help of artificial neural network predictor.

The mathematical model of the pump. Regarding control, the water supply and overflow-pipe systems are difficult technological complexes, for research of which mathematical models of different complication levels are used. The water supply system is a nonlinear system with varying in time parameters and considerable quantity of variables. Most researchers use a simplified model of this system based on a second order transfer function, or more detailed model based on a separate description of every element of the system.

In our case we use the model of the pump that is based on approximation of head vs. flow-rates characteristics by the equation [4]

$$H_n(t) = a\nu^2(t) + b\nu(t)Q(t) + cQ^2(t), \qquad (1)$$

where $H_n(t)$ is the output head of the pump; $\nu(t)$ is the relative rotation speed; $Q(t)$ is the flow rate; a, b, c are the approximation coefficients.

The dynamics of the pump is described by the first-order transfer function

$$\frac{dH_1(t)}{dt}=\frac{H_n(t)-H_1(t)}{T_n}. \qquad (2)$$

Then the loading torque of the pump drive motor is determined as

$$M_c(t)=\frac{\rho gQ(t)H_n(t)}{\eta\omega(t)}, \qquad (3)$$

where $\rho = 1000$ kg/m^3 is water density; η is the coefficient of pump efficiency; ω is the angular speed of the motor.

To simulate a hydraulic network, the model, offered in [8, 9] is used

$$\begin{aligned}\frac{dQ_1(t)}{dt}&=\frac{1}{l_1}\left(H_1(t)-H_2(t)-r_1Q_1^2(t)\right);\\ \frac{dH_2(t)}{dt}&=C_1\left(Q_1(t)-Q_2(t)\right),\end{aligned} \qquad (4)$$

where $H_1(t)$, $H_2(t)$ are the heads at the input and output of the pipeline section; $Q_1(t)$, $Q_2(t)$ stand for the flowrate in the neighbouring sections of the pipeline; r_1 is the hydraulic resistance of the hydraulic network's section; $l_1 = l_{01}/(Sg)$, where l_{01}, S is the length and the sectional area of the pipeline. The long hydraulic network is represented as a series connection of such pipeline sections.

In order to create the model of a frequency-controlled electric drive the object-oriented method described in [10] is used. The object-model of induction-squirrel-cage motor (IM) realizes a mathematical model in phase coordinates. The calculation scheme of the induction machine is presented as multipole (Fig. 3). For this scheme the equation of electric balance, written in a vector-matrix form, is the following

$$\vec{\varphi}_1-\vec{\varphi}_2+\breve{R}_{am}\vec{i}_m+\frac{d\vec{\Psi}_{am}}{dt}, \qquad (5)$$

where $\vec{\varphi}_1=\left(\varphi_{A1},\varphi_{B1},\varphi_{C1},\varphi_{a1},\varphi_{b1},\varphi_{c1}\right)_t$, $\vec{\varphi}_2=(\varphi_{A2},\varphi_{B2},\varphi_{C2},$ φ_{a2}, φ_{b2}, $\varphi_{c2})_t$ are the vectors of potentials of external poles of the multipole; $\vec{i}_m=\left(i_A,i_B,i_C,i_a,i_b,i_c\right)_t$ are the vectors of currents of external branches of the multipole, i.e. currents in the stator and rotor; $\breve{R}_{\grave{a}m}=$ $=diag\left(r_A,r_B,r_C,r_a,r_b,r_c\right)$ is the diagonal matrix of resistances of the stator and rotor windings; $\vec{\Psi}_{\grave{a}m}=$ $=\left(\psi_A,\psi_B,\psi_C,\psi_a,\psi_b,\psi_c\right)_t$ is the vector of flux linkages of the stator and rotor windings.

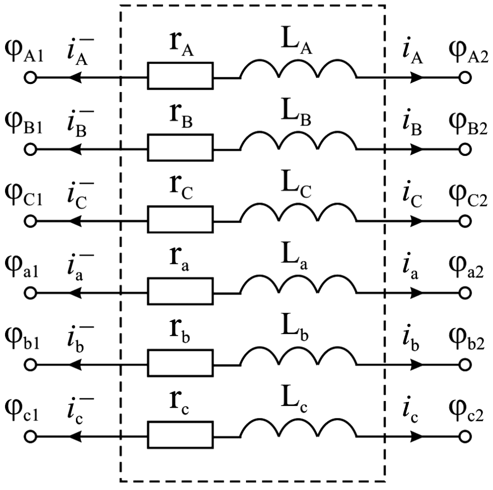


Fig. 3. The calculation scheme of induction machine

The flux linkages in (5) are the functions of currents of all phases of the stator and rotor, as well as of the rotor angle γ_{am}. Accordingly, for the flux linkage of a stator phase A it is possible to write

$$\begin{aligned}\frac{d\psi_A}{dt}&=\frac{\partial\psi_A}{\partial i_A}\frac{di_A}{dt}+\frac{\partial\psi_A}{\partial i_B}\frac{di_B}{dt}+\frac{\partial\psi_A}{\partial i_C}\frac{di_C}{dt}+\frac{\partial\psi_A}{\partial i_a}\frac{di_a}{dt}+\\ &+\frac{\partial\psi_A}{\partial i_{b\grave{a}m}}\frac{di_b}{dt}+\frac{\partial\psi_A}{\partial i_c}\frac{di_c}{dt}+\frac{\partial\psi_A}{\partial\gamma}\frac{d\gamma}{dt}.\end{aligned}$$

In the obtained equation, the partial derivatives of flux linkages according to currents are the dynamic inductances which, in this case, are presented as static inductances, in particular by self-inductance of stator phase A and mutual inductances between phases of IM windings. Then, it is possible to write the following in a vector-matrix form

$$\frac{d\vec{\Psi}_{\grave{a}m}}{dt}=\breve{L}_{\grave{a}m}\frac{d\vec{i}_m}{dt}+\frac{d\vec{\Psi}_{\grave{a}m}}{d\gamma_{\grave{a}m}}p_0\omega=\breve{L}_{\grave{a}m}p\vec{i}_m+\frac{d\breve{L}_{\grave{a}m}}{d\gamma_{\grave{a}m}}\vec{i}_mp_0\omega, \qquad (6)$$

where p_0 is the number of pole pairs; ω is the rotor angular speed; $\breve{L}_{am}$ is the matrix of self- and mutual inductances of IM windings

$$\breve{L}_{\grave{a}m}=\begin{bmatrix}L_{AA} & L_{AB} & L_{AC} & L_{Aa} & L_{Ab} & L_{Ac}\\ L_{BA} & L_{BA} & L_{BC} & L_{Ba} & L_{Bb} & L_{Bc}\\ L_{CA} & L_{CB} & L_{CC} & L_{Ca} & L_{Cb} & L_{Cc}\\ L_{aA} & L_{aB} & L_{aC} & L_{aa} & L_{ab} & L_{ac}\\ L_{bA} & L_{bB} & L_{bC} & L_{ba} & L_{bb} & L_{bc}\\ L_{cA} & L_{cB} & L_{cC} & L_{ca} & L_{cb} & L_{cc}\end{bmatrix},$$

where the self-inductances of the stator windings are equal to $L_{AA}=L_{BB}=L_{CC}=L_m+L_{\sigma s}+\frac{L_{0s}}{2}$; the self-inductances of the rotor windings are equal to $L_{aa}=L_{bb}=L_{cc}=\frac{-L_m-L_{\sigma r}+L_{0r}}{2k^2}$; the mutual inductances between the phases of the stator winding are equal to

$$L_{AB}=L_{AC}=L_{BA}=L_{CA}=L_{BC}=L_{CB}=\frac{-L_m-L_{\sigma s}+L_{0s}}{2};$$

the mutual inductances between the phases of the stator and rotor windings depend on the rotor angle γ_{am} and are equal to

$$\begin{gathered}L_{aA}=L_{Aa}=\frac{L_m}{k}\cos\left(\gamma_{am}\right);\\ L_{Ab}=L_{bA}=\frac{L_m}{k}\cos\left(\gamma_{am}+\rho\right);\\ L_{Ac}=L_{cA}=\frac{L_m}{k}\cos\left(\gamma_{am}-\rho\right)\end{gathered}$$

(other mutual inductances are determined analogously); L_m is magnetizing inductance; $L_{\sigma s}$, $L_{\sigma r}$ are leakage inductances of the stator and rotor windings; L_{0s}, L_{0r} are zero-sequence inductances of the stator and rotor; k is transformation ratio between the stator and rotor winding; $\rho = 2\pi/3$.

To consider non-linearity of a magnetizing characteristic the magnetizing inductance L_m is determined as a quotient of the flux linkage module ψ_m to the magnetizing current i_μ

$$L_m = \psi_m / i_\mu.$$

The electromagnetic torque of induction motor is defined as

$$M = \frac{3}{2} p_0 L_m \left(i_{r\beta} i_{s\alpha} - i_{r\alpha} i_{s\beta} \right),$$

where $i_{s\alpha}$, $i_{s\beta}$, $i_{r\alpha}$, $i_{r\beta}$ are the currents of the stator and rotor in the rectangular stationary $\alpha\beta$ coordinate system which are determined on the basis of the phase currents from the known formulas of coordinates transformation.

The rotate speed of the rotor of induction motor is determined from the mechanical balance equation

$$\frac{d\omega}{dt} = (M - M_c)/J.$$

In order to simplify the system model, the power network and frequency converter are presented by the object-model of the controlled source with changeable voltage and frequency.

During the research the following parameters of equipment are used: for the pump they are: power rating $P = 760$ kW, coefficient of efficiency $\eta = 0.75$, nominal flow rate $Q_n = 0.556$ m^3/c, nominal head $H_n = 100$ m; for induction motor they are: $P_m = 800$ kW, nominal rotational speed $n_n = 1500$ rpm, nominal voltage $U_n = 6000$ V, nominal current $I_n = 94.5$ A, moment of inertia $J = 38$ kg/m^2, magnetizing inductance $L_m = 0.3$ H, leakage inductances of the stator and rotor winding $L_{\sigma 1} = L'_{\sigma 2} = 0.011$ H, resistance of the stator and rotor winding $R_1 = 0.512$ Om, $R'_2 = 0.53$ Om; those for hydraulic network are: $a = 118$, $b = -20.38$, $c = -94.88$, $T_n = 0.1$, $l_1 = 20.28$, $r_1 = 0.62$, $C_1 = 4264$.

The research results for the dynamic modes in the "frequency-controlled induction drive – pump – pipeline" systems are shown in Figs 4–10 as the time dependences of basic coordinates for the flow-rate changing from $0.2Q_n$ to $Q_н$ (Fig. 4). The main task of the pressure control system, in this case, is pressure stabilization (head) on the set level (70 m). Considering the pipeline parameters distribution, the pipeline output head (Fig. 6) differs from the pipeline input head in some degree (Fig. 5), namely: with the increasing distance from the pump, on the exit of which pressure is regulated, the pressure oscillation increases. At the output of the pipeline pressure decline occurs; a drop of pressure in the pipeline section is proportional to a square of a water flow rate. The pressure of the pump is stabilized by the control system with PI-controller of pressure, the output signal of which sets the frequency of the IM supply

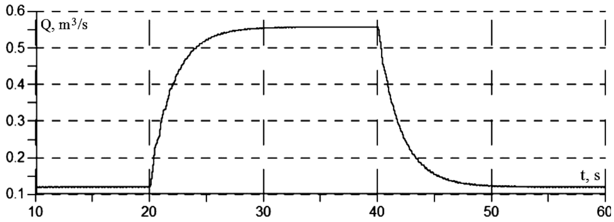


Fig. 4. The water flow rate Q

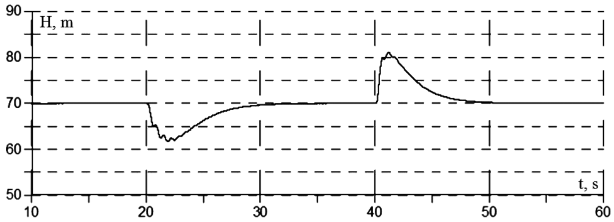


Fig. 5. The head H at the pump input

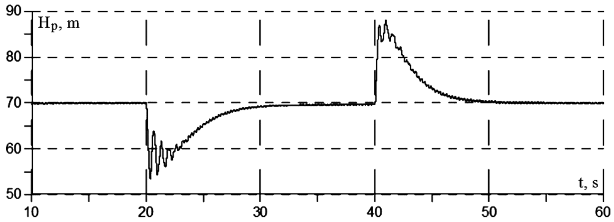


Fig. 6. The head H_T at the pipeline output

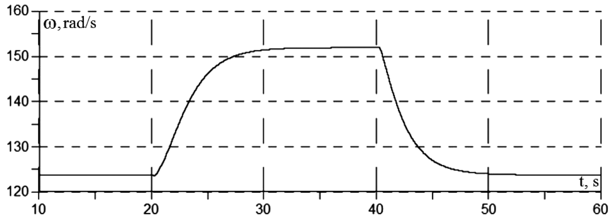


Fig. 7. The angular speed of IM ω

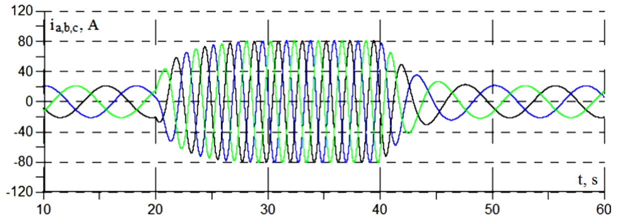


Fig. 8. The rotor current i_a, i_b, i_c conveyed to the stator winding (instantaneous values)

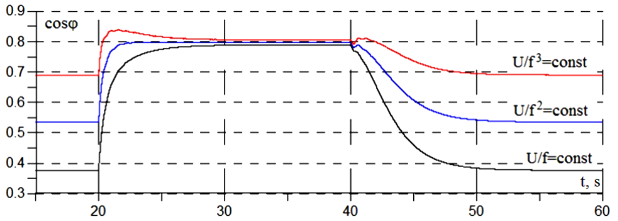


Fig. 9. The power factor of the electric drive in case of flow rate changing $0.2Q_n$ – Q_n - $0.2Q_n$ and for the use of the different frequency control laws

voltage and, accordingly, the rotation speed. The value of IM supply voltage, in this case, is determined by the frequency regulation law. The IM rotor current (Fig. 8) is determined by slip, accordingly the amplitude and the frequency of the rotor current are increasing with the flow rate increasing.

The chosen frequency control law determines a change of the power-factor of the electric drive under the flow rate changing (Fig. 9). The use of the frequency control law $U/f^2 = \text{const}$ gives an opportunity to increase a power-factor in case of the flow rate decreasing. The best result, for this system, in terms of providing the maximal power-factor, gives the use of the frequency control law $U/f^3 = \text{const}$, at which the maximal reduction of magnetic flux and magnetizing current occurs for a low rotation speed of IM (under a low flow rate).

In order to consider the real character of the flow rate changing within 24 hours, the schedule of the water consumption was experimentally obtained from the taken off hourly data (Fig. 10). While estimating, the real character of daily flow rate changing was modelled by dependence in reduced scale of time. This dependence (Fig. 11) was obtained from the output of the intensity selector, the input signal of which were jumping, according to the real flow rate values, taken once every hour.

In Fig. 12 the water flow-rate predicted by neuropredictor also is shown.

The research results for the dynamic modes in the pressure regulation system regarding the real chart of flow rate changing are shown in Fig. 12. The research was carried out for the pressure set point signal changing proportionally to the predicted flow rate $H_{sp} = H_{sp0} + \kappa_1 Q_{pr.}$ and proportionally to a square of the predicted flow rate $H_{sp} = H_{sp0} + \kappa_1 Q^2_{pr.}$ For the purpose of the comparative analysis, the traditional system with the permanent pressure set point signal was studied. For all cases the scalar control law $U/f^2 = \text{const}$ was realized.

The automatic control system provides the astatic regulation of the pressure (Fig. 12, *a*). As the research results show, the reduction of the head in the system with the flow rate prediction gives an opportunity to decrease the consumption of active-power by the pump

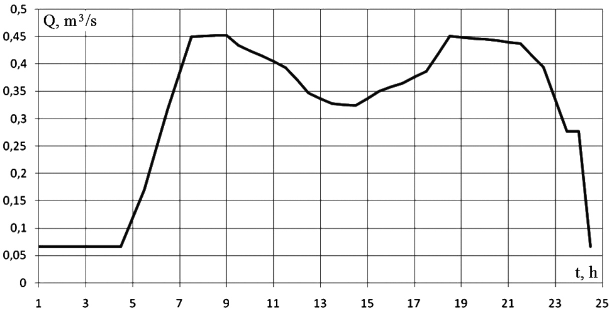


Fig. 10. The real chart of the water consumption Q within 24 hours

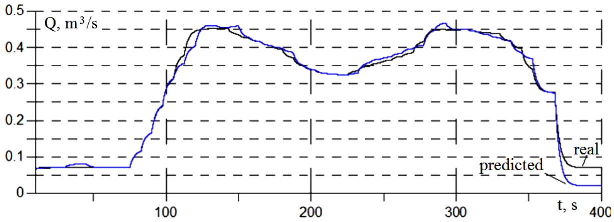
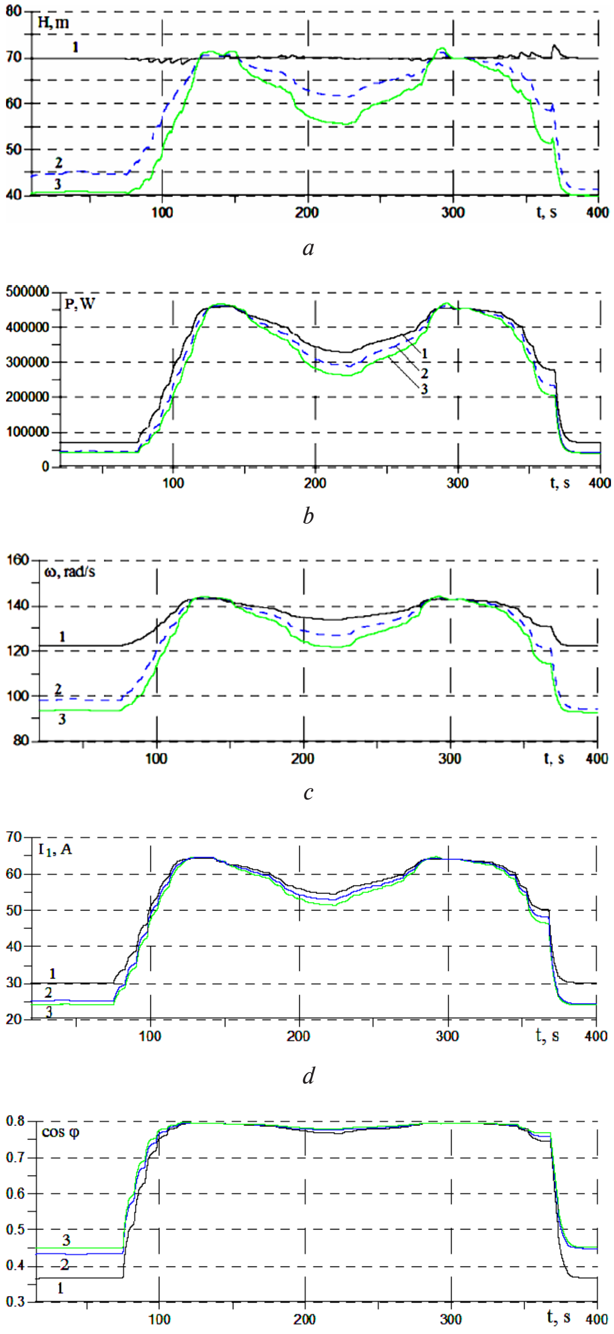


Fig. 11. The water flow rate Q: the real and the predicted by neuropredictor



a

b

c

d

e

Fig. 12. The heat at the pump output H (a), the consumed active power of the pump P (b), the pump rotation speed ω (c), the current of IM I_1 stator (d), the power factor of the electric drive cos φ (e) for the frequency control laws:

1 – $H = \text{const}$; 2 – $H_{sp} = H_{sp0} + \kappa_1 Q_{pred}$; 3 – $H_{sp} = H_{sp0} + \kappa_1 Q^2_{pred}$

drive (Fig. 12, *b*). The reduction of pressure at a small value of flow rate is attained by decrease in the IM speed (Fig. 12, *c*). The stator current (Fig. 12, *d*) decreases both due to reduction of active constituent according to reduction of IM load and reactive constituent that decreases according to the stator voltage decreasing proportionally to the square of frequency, and, accordingly, to the IM magnetic flux. The decrease in the magnetic flux and magnetizing current under the frequency reduction provides increasing of the electric drive power-factor (Fig. 12, *e*).

Conclusions. The research results allow asserting that the electric drive control system with the artificial neural network predictor permits decreasing the consumption of active-power and increasing the power-factor of electric drive compared to the system with permanent set point pressure; notably, the system in which a set point signal changes proportionally to the square of the predicted flow rate value has a higher efficiency.

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Мета. Обґрунтування використання нейропредикторів у системах керування насосами систем водопостачання для прогнозування величини витрати впродовж доби.

Методика. Шляхом експериментальних досліджень на діючій системі водопостачання отримані дані для синтезу нейропредиктора. Із застосуванням об’єктно-орієнтованого методу створена математична модель системи електропривода насоса, що враховує нелінійність характеристики намагнічування магнітопроводу асинхронної машини та наявність гідравлічної мережі з розподіленими параметрами на виході насоса. Із застосуванням розробленої математичної моделі шляхом комп’ютерного симулювання досліджені режими частотного регулювання асинхронного електропривода насоса, динамічні режими роботи електропривода у випадку прогнозованих витрат та якісні показники регулювання тиску.

Результати. На основі експериментально отриманих даних синтезовано нейропредиктор, що адекватно прогнозує величину споживаної впродовж доби води. Синтезована система керування насосом з нейропредиктором, що реалізує різні закони регулювання тиску на виході насосу. Обґрунтовано закони частотного регулювання для електропривода насоса.

Наукова новизна. Уперше в системі керування насосом запропоноване використання нейропредиктора для прогнозування величини витрати та синтезу керуючих впливів на електропривод насосу з урахуванням величини прогнозованого споживання води. Отримані результати, що демонструють взаємний вплив процесів у водопровідній мережі та електромагнітних процесів в асинхронному електроприводі.

Практична значимість. Завдяки врахування прогнозованої величини водоспоживання в запропонованій системі керування насосом підвищується енергоефективність системи водопостачання та зменшуються непродуктивні втрати води.

Ключові слова: *насос, нейропредиктор, асинхронний електропривод, математичне моделювання*

Цель. Обоснование использования нейропредикторов в системах управления насосами систем водоснабжения для прогнозирования величины расхода на протяжении суток

Методика. Путем экспериментальных исследований на действующей системе водоснабжения получены данные для синтеза нейропредиктора. С применением объектно-ориентированного метода создана математическая модель системы электропривода насоса, учитывающая нелинейность характеристики намагничивания магнитопровода асинхронной машины и наличие гидравлической сети с распределенными параметрами на выходе насоса. С использованием разработанной модели путем компьютерной симуляции исследованы режимы частотного регулирования асинхронного электропривода насоса, динамические режимы работы электропривода для прогнозируемого расхода и качественные показатели регулирования давления.

Результаты. На основании экспериментально полученных данных синтезирован нейропредиктор, адекватно прогнозирующий величину потребляемой за сутки воды. Синтезирована система управления насосом с нейропредиктором, реализующая различные законы регулирования давления на выходе насоса. Обоснованы законы частотного регулирования для электропривода насоса.

Научная новизна. Впервые в системе управления насосом предложено использование нейропредиктора для прогнозирования величины расхода и синтеза управляющих воздействий на электропривод насоса с учетом величины прогнозируемого расхода воды. Получены результаты, демонстрирующие взаимное влияние процессов в водопроводной сети и электромагнитных процессов в асинхронном электроприводе.

Практическая значимость. Благодаря учету прогнозируемой величины водопотребления в предложенной системе управления насосом повышается энергоэффективность системы водоснабжения и уменьшаются непродуктивные потери воды.

Ключевые слова: *насос, нейропредиктор, асинхронный электропривод, математическое моделирование*

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