Algorithms of synthesis the adaptive control system based on reference model for technological plant

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Abstract. The stages of synthesis and structural analysis of an adaptive control system based on a reference model for dynamic plants are presented this research. The parameters of the dynamic plant under consideration are calculated in the form of a common matrix. To add the parameters of the reference model are being in kind of matrix. The use of adaptive control algorithms directly connects the process of determining plant parameters with the automatic adjustment of actuators in reference-based control systems. The concept of error vector is derived from the adaptive assessment of the control system based on the reference model. The error vector is presented as a general representation of the difference between the reference model input and the plant input in the form of a matrix. Adjustment steps aimed at reducing this difference are considered. This control system is synthesized into the technological process of natural gas purification based on method of absorption and certain results are obtained.

INTRODUCTION

Adaptive control systems allow for high-efficiency and high-precision control of complex technological processes. They ensure stable operation in the face of uncertain environmental influences, sharp fluctuations in system parameters, and unexpected disruptions in the operating mode. The main advantage of such systems is that they quickly detect changes in the control plant in real time and develop optimal control decisions based on algorithms for adapting the system to new values. As a result, adaptive systems minimize the negative consequences of external influences while maintaining the dynamic characteristics of the process.

I. Synthesis adaptive control systems based on a reference model into technological plant

From the researches, it can be seen that the use of adaptive control algorithms directly connects the process of determining the parameters of the plant with the automatic adjustment of actuators in feedback-based control systems. In this approach, the actuator settings are dynamically updated in real time in accordance with changes in the parameters of the controlled plant. The use of adaptive control increases the functional flexibility of actuators, significantly increasing the reliability and efficiency of the system [6]. In particular, in recent years, research on the design and optimization of control systems aimed at increasing energy efficiency has been developing rapidly. This area is currently at the center of current scientific and practical research, as adaptive approaches based on automatic tuning of regulators allow for significant reductions in energy consumption [8].

The analysis of the adaptive properties requires, first of all, the definition of the problem of tuning the adaptive control system for the transition process based on the synthesized reference model algorithm in the control system. In this process, it is also important not only to find this solution, but also to assess its reliability in terms of its correctness and practical application. Linear and continuous control systems have been widely studied in many scientific sources [3]. This study is aimed at analyzing the mechanisms that ensure adaptability in the control of linear continuous technological processes, in particular, the complex dynamic properties of control plants with multiple inputs and multiple outputs are studied in depth. In cases where the control plant is linear, even if the adjuster has a general characteristic, it is necessarily based on a specific linear structure.

The equation of a linear control system, presented in the following general matrix form is considered:

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix}=\begin{bmatrix}T_{11} & 0\\ T_{21} & T_{22}\end{bmatrix}\cdot\begin{bmatrix}x_1\\ x_2\end{bmatrix}+\begin{bmatrix}H\\ 0\end{bmatrix}\cdot u$$

$$y=\begin{bmatrix}C_1 & C_2\end{bmatrix}\cdot\begin{bmatrix}x_1\\ x_2\end{bmatrix} \tag{1}$$

The vectors of the plant control based on reference model are depicted in the following form:

$$\begin{bmatrix}\dot{x}_{E1}\\ \dot{x}_{E2}\end{bmatrix}=\begin{bmatrix}E_{11} & 0\\ E_{21} & E_{22}\end{bmatrix}\cdot\begin{bmatrix}x_{E1}\\ x_{E2}\end{bmatrix}+\begin{bmatrix}H_E\\ 0\end{bmatrix}\cdot u_E$$

$$y_E=\begin{bmatrix}C_{E1} & C_{E2}\end{bmatrix}\cdot\begin{bmatrix}x_{E1}\\ x_{E2}\end{bmatrix}. \tag{2}$$

When assessing the adaptability of the current adjustment algorithms in the plant control system, the difference between the real process coefficients and the reference model is determined depending on whether it is large or small. In plant control, the operating mode coefficients are synthesized based on the approximation of the vectors or matrices of the reference model. That is, $x_1=x_{E1},\ x_2=x_{E2},....,x_s=x_{Es}$ a condition of necessity is determined in connection with the fulfillment of equality. This condition of necessity is expressed using a pseudo-inverse matrix H^+ and has the following form:

$$HH^+\begin{bmatrix}T_{11}-E_{11} & 0\\ T_{21}-E_{21} & T_{22}-E_{22}\end{bmatrix}=\begin{bmatrix}T_{11}-E_{11} & 0\\ T_{21}-E_{21} & T_{22}-E_{22}\end{bmatrix},\ HH^+H_E=H_E, \tag{3}$$

The result of writing this expression in matrix color form is as follows:

$$rangH=rang(H,\ H_E) \tag{4}$$

When assessing the adaptability of adjustment algorithms to an plant control system, the concept of an error vector is introduced. The error vector is a matrix representation of the difference between the reference model input and the plant input.

$$\begin{bmatrix}\omega_1\\ \omega_2\end{bmatrix}=\begin{bmatrix}x_1-x_{E1}\\ x_2-x_{E2}\end{bmatrix} \tag{5}$$

Using the expressions given above, the first-order derivative of the error vector can be written in full form as follows:

$$\begin{bmatrix}\dot{\omega}_1\\ \dot{\omega}_2\end{bmatrix}=\begin{bmatrix}\dot{x}_1-\dot{x}_{E1}\\ \dot{x}_2-\dot{x}_{E2}\end{bmatrix}=\begin{bmatrix}T_{11} & 0\\ T_{21} & T_{22}\end{bmatrix}\cdot\begin{bmatrix}x_1\\ x_2\end{bmatrix}+\begin{bmatrix}H\\ 0\end{bmatrix}\cdot u-\begin{bmatrix}E_{11} & 0\\ E_{21} & E_{22}\end{bmatrix}\cdot\begin{bmatrix}x_{E1}\\ x_{E2}\end{bmatrix}+\begin{bmatrix}H_E\\ 0\end{bmatrix}\cdot u_E. \tag{6}$$

This expression is expressed as a general differential matrix, called the error matrix in the adaptive estimation:

$$\begin{bmatrix}\dot{\omega}_1\\ \dot{\omega}_2\end{bmatrix}=\begin{bmatrix}E_{11} & 0\\ E_{21} & E_{22}\end{bmatrix}\cdot\begin{bmatrix}\omega_1\\ \omega_2\end{bmatrix}. \tag{7}$$

If this equation is written for a system with more than two variables, the expression becomes general as follows:

$$\begin{bmatrix}\dot{\omega}_1\\ \dot{\omega}_2\\ \cdots\\ \dot{\omega}_s\end{bmatrix}=\begin{bmatrix}E_{11} & E_{12} & \cdots & E_{1k}\\ E_{21} & E_{22} & \cdots & E_{2k}\\ \cdots & \cdots & \cdots & \cdots\\ E_{s1} & E_{s2} & \cdots & E_{sk}\end{bmatrix}\cdot\begin{bmatrix}\omega_1\\ \omega_2\\ \cdots\\ \omega_s\end{bmatrix} \tag{8}$$

Using the Laplace transform, the above matrix can be transformed into the following system of equations:

$$\begin{bmatrix}s\omega_1(s)\\ s\omega_2(s)\\ \cdots\\ s\omega_s(s)\end{bmatrix}=\begin{bmatrix}E_{11} & E_{12} & \cdots & E_{1k}\\ E_{21} & E_{22} & \cdots & E_{2k}\\ \cdots & \cdots & \cdots & \cdots\\ E_{s1} & E_{s2} & \cdots & E_{sk}\end{bmatrix}\cdot\begin{bmatrix}\omega_1(s)\\ \omega_2(s)\\ \cdots\\ \omega_s(s)\end{bmatrix},\ \text{or} \tag{9}$$

$$\begin{cases} \omega_1(s)(s-E_{11})+\omega_2(s)(s-E_{12})+....+\omega_s(s)(s-E_{1k})=0 \\ \omega_1(s)(s-E_{21})+\omega_2(s)(s-E_{22})+....+\omega_s(s)(s-E_{2k})=0 \\ \\ \omega_1(s)(s-E_{s1})+\omega_2(s)(s-E_{s2})+....+\omega_s(s)(s-E_{sk})=0 \end{cases}$$

The solution to this system of equations is expressed by the following equation.

$$\omega_1=\omega_2=.... =\omega_E=0 \quad (10)$$

From this, it can be concluded that the difference between the real-time plant input value and the value obtained in the reference model is zero. Thus, the adaptiveness of the synthesized adjustment algorithms to the plant control system is assessed as high.

The difference between the output signal of the adjustment algorithms and the output of the reference model when synthesizing them into the plant control system is called the total control error. This control error can be expressed as follows:

$$\partial(t)=y-y_E \quad (11)$$

The condition for optimal synthesis of adjustment algorithms into an plant control system can be stated as follows:

$$\partial=\lim_{t\to\infty}(y-y_E)=0 \quad (12)$$

In the stages of synthesizing an adaptive control system based on the benchmark model algorithm for continuous linear dynamic plants, one faces the problem of solving several higher-order differential equations. However, using artificial neural network technologies, this operation is somewhat simplified and leads to an improvement in the quality of the adjustment. In the following sections, neural network technologies and their algorithms for training, control, and error reduction in the synthesis of such adaptive control systems for technological plants will be considered.

II. Determination of transfer function coefficients in adaptive control systems

Let the input and output functions of the plant control equation and the coefficient matrices be given as follows:

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix}=\begin{bmatrix}T_{11} & 0\\ T_{21} & T_{22}\end{bmatrix}\cdot\begin{bmatrix}x_1\\ x_2\end{bmatrix}+\begin{bmatrix}\frac{k}{A_1}\\ 0\end{bmatrix}\cdot u \quad (13)$$

$$y=[0\ \ 1]\cdot\begin{bmatrix}x_1\\ x_2\end{bmatrix} \quad (14)$$

To generalize this space equation of state, the following notations are introduced:

$$A=\begin{bmatrix}T_{11} & 0\\ T_{21} & T_{22}\end{bmatrix},\quad B=\begin{bmatrix}\frac{k}{A_1}\\ 0\end{bmatrix},\quad C=[0\ \ 1],\quad D=0. \quad (15)$$

The result of expressing the control equation of a linear system in the form of a transfer function is as follows:

$$TrF(p)=\frac{Y(p)}{X(p)}=C(pI-A)^{-1}B+D \quad (16)$$

Here *I* is the identity matrix. From this we get the following matrix.

$$pI=\begin{bmatrix}p & 0\\ 0 & p\end{bmatrix}. \quad (17)$$

Describing the linear model of the control plant in the form of the following transfer function:

$$TrF(p)=[0\ \ 1]\cdot\left(\begin{bmatrix}p & 0\\ 0 & p\end{bmatrix}-\begin{bmatrix}T_{11} & 0\\ T_{21} & T_{22}\end{bmatrix}\right)^{-1}\cdot\begin{bmatrix}\frac{k}{A_1}\\ 0\end{bmatrix}; \quad TrF(p)=[0\ \ 1]\cdot\left(\begin{bmatrix}p-T_{11} & 0\\ -T_{21} & p-T_{22}\end{bmatrix}\right)^{-1}\cdot\begin{bmatrix}\frac{k}{A_1}\\ 0\end{bmatrix}$$

$$TrF(p)=[0\ \ 1]\cdot\left(\frac{adj\begin{bmatrix}p-T_{11} & 0\\ -T_{21} & p-T_{22}\end{bmatrix}}{\begin{vmatrix}p-T_{11} & 0\\ -T_{21} & p-T_{22}\end{vmatrix}}\right)\cdot\begin{bmatrix}\frac{k}{A_1}\\ 0\end{bmatrix}; \quad TrF(p)=[0\ \ 1]\cdot\left(\frac{\begin{bmatrix}p-T_{22} & 0\\ -T_{21} & p-T_{11}\end{bmatrix}}{p^2+(-T_{11}-T_{22})p+T_{11}T_{22}}\right)\cdot\begin{bmatrix}\frac{k}{A_1}\\ 0\end{bmatrix}$$

$$TrF(p)=[0\quad 1]\cdot[\frac{\begin{bmatrix}(p-T_{22})\cdot\frac{k}{A_1}\\ T_{21}\left(\frac{k}{A_1}\right)\end{bmatrix}}{p^2+(-T_{11}-T_{22})p+T_{11}T_{22}}];\quad TrF(p)=\left[\frac{(0)\cdot(p-T_{22})\cdot\left(\frac{k}{A_1}\right)+(1)\cdot T_{21}\left(\frac{k}{A_1}\right)}{p^2+(-T_{11}-T_{22})p+T_{11}T_{22}}\right]. \tag{18}$$

Final view transfer function for a linear plant:

$$TrF(p)=\frac{T_{21}\left(\frac{k}{A_1}\right)}{p^2+(-T_{11}-T_{22})p+T_{11}T_{22}}. \tag{19}$$

To stabilize the developed linear model, the model is described in the form of a suitable adaptive PID tuning system. To simplify the mathematical derivation of the adaptive PID tuner, the expression of the transfer function of the final linear model is written as.

$$W(p)=\frac{k_3}{k_0p^2+k_1p+k_2}, \tag{20}$$

$$TrF(p)=W(p);\quad k_0=1;\quad k_1=(-T_{11}-T_{22});\quad k_2=T_{11}T_{22};\quad k_3=T_{21}\left(\frac{k}{A_1}\right). \tag{21}$$

III. Structural analysis of adaptive control systems based on a reference model in the synthesis of technological plants.

Adaptive system based on a parallel-connected reference module. An optimal reference module is developed for the system. It works by comparing the values in the operating mode to the reference module.

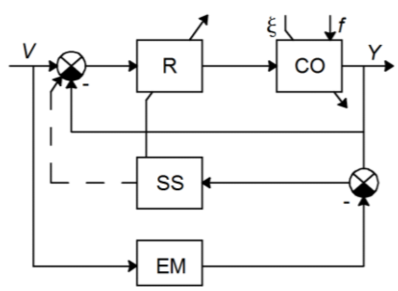

FIGURE 1. Structural diagram of an adaptive system based on a parallel-connected reference module.

An adaptive system based on a series-connected reference module:

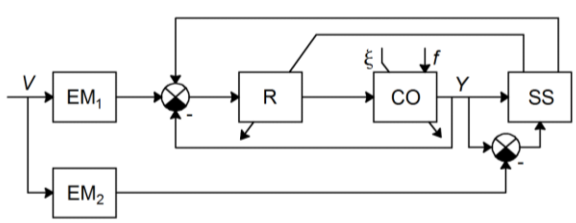

FIGURE 2. Structural diagram of an adaptive system based on a series-connected reference module.

The following tasks are relevant in creating an adaptive control system: synthesis of adaptive control systems for multi-channel and multi-mode objects operating under conditions of various types of variable deviations. development and justification of methods for simplifying the structures of adaptive control devices. improvement of the established quality indicators for transient and stable processes.

The purpose of creating an adaptive control system is to control multi-channel and multi-mode objects. At the same time, it is necessary to analyze adaptive control systems and create theoretical foundations for the synthesis of adaptive control systems aimed at improving the quality of work in conditions of uncontrolled variable deviations.

IV. Algorithms of Narma-L2 for identification neural network model.

As in the system informed on the prediction algorithm, the first stage of the Narma-L2 neural network is the identification of the control plant. The Narma-L2 models equation are formed by approximating the "nonlinear autoregressive moving average model" (Narma – nonlinear autoregressive moving average) equation 21.

$$\begin{aligned}\hat{y}(t+\tau) &= f[y(t), y(t-1),..., y(t-a+1), x(t), x(t-1),..., x(t-n+1)] + \\ &g[y(t), y(t-1),..., y(t-a+1), x(t), x(t-1),..., x(t-n+1)] \cdot u(t)\end{aligned} \tag{22}$$

In this model, an additional function is introduced, taking into account the nonlinear characteristics of the plant. figure 6 shows the structural scheme of the Narma-L2 neural network. In the given structure of $f(x)$ and $g(x)$, the functions and are added to the system as separate sub-network blocks.

In the Narma-L2 model, the control signal is calculated by dividing the system output by the control signal $y(t+\tau) = y_r(t+\tau)$. The control signal from the model is calculated using the following expression.

$$u(t) = \frac{y_r(t+\tau) - f[y(t), y(t-1),..., y(t-a+1), x(t), x(t-1),..., x(t-n+1)]}{g[y(t), y(t-1),..., y(t-a+1), x(t), x(t-1),..., x(t-n+1)]} \tag{23}$$

In this relationship, the delay time is taken as $\tau \geq 1$. Figure 3 shows the structure of the control system modeled after the Narma-L2 neural network.

V. Neural network algorithms based on the reference model in control systems

Another key algorithm that is synthesized into a plant control system using neural network technology is the reference model-based network. This algorithm uses two neural networks. These networks are represented as a control network and a plant model. Figure 3 shows the structural diagram of a reference model-based control system. In the first stage of the algorithm under consideration, a plant model is determined, and then the neural network in the control system is trained on the plant output.

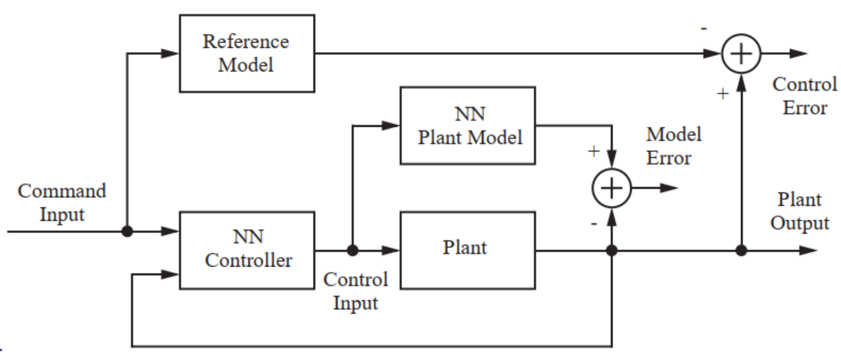

FIGURE 3. Control system rooted in reference model.

A networks modeled after a reference model are synthesized into a plant model as a control system and the minimum error mode is calculated. The control system synthesized into the plant is constantly compared with the reference model. This serves to bring the neural network in the approximated control system closer to the reference network.

In the figure 4, the architectures of the neural network plant model, the control system with the neural network reference model interconnection are demonstrated. There are three sets of networks in the control system. These networks are: the reference model input with delay, the output from the control system model (inputs to the plant), and the output from the plant model. The delay values are chosen separately for all parameters in the system. Typically, the delay values are chosen in relation to the order of the network representing the plant model. The neural network representing the plant model has two input networks: the control network outputs with delay and the plant output.

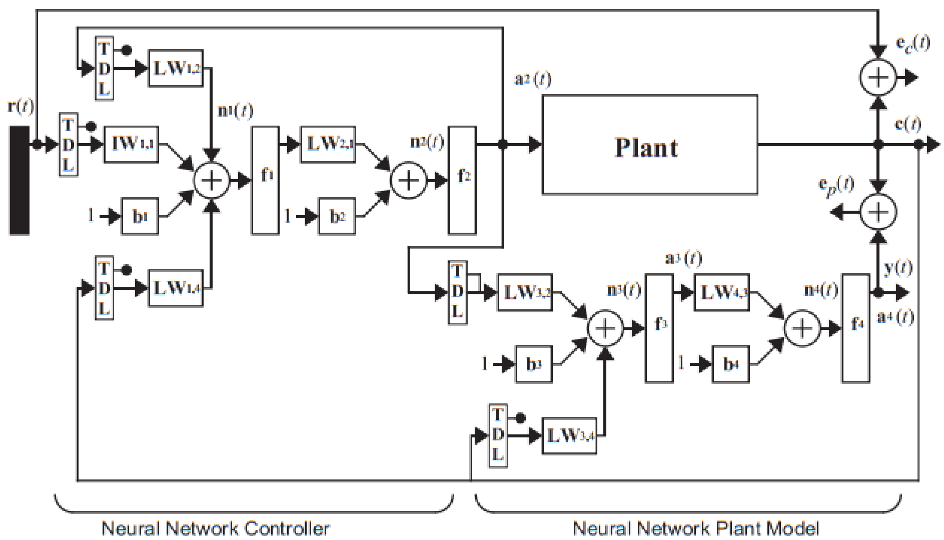

FIGURE 4. Structural diagram of the synthesis of a system derived from a reference model into a control plant.

The general equations for identifying a neural network system derived from a reference model are written using the following equation:

$$y(t+\tau) = A_p[y(t), y(t-1), \ldots, y(t-a+1), x(t), x(t-1), \ldots, x(t-n+1)] \tag{24}$$

This relationship is the general equation for implementing the identification steps of a neural network founded on the two algorithms discussed above: predictive and nonlinear autoregressive average moving average (Narma) models. The synthesis steps of this equation are also implemented in a network rooted in a reference model. However, synthesizing a neural network based on a reference model into a control system is much more complicated.

VI. Synthesis of a control system based on a reference model for controlling the parameters of the absorption technological process.

For this system under study, adaptive control systems of parameters in the technological process of natural gas absorption purification are taken as a dynamic object.

In modern automatic control theory, the synthesis of adaptive systems controlled by scalar outputs is an important category of problems, which leads to theoretical problems in the synthesis of systems [6]. In some special cases, the solution is carried out using several methods. These include shunting, extended errors, and higher-order adaptation methods.

Taking the absorption column structure under study as a control object, a structural scheme is built using a calibration system based on a reference model.

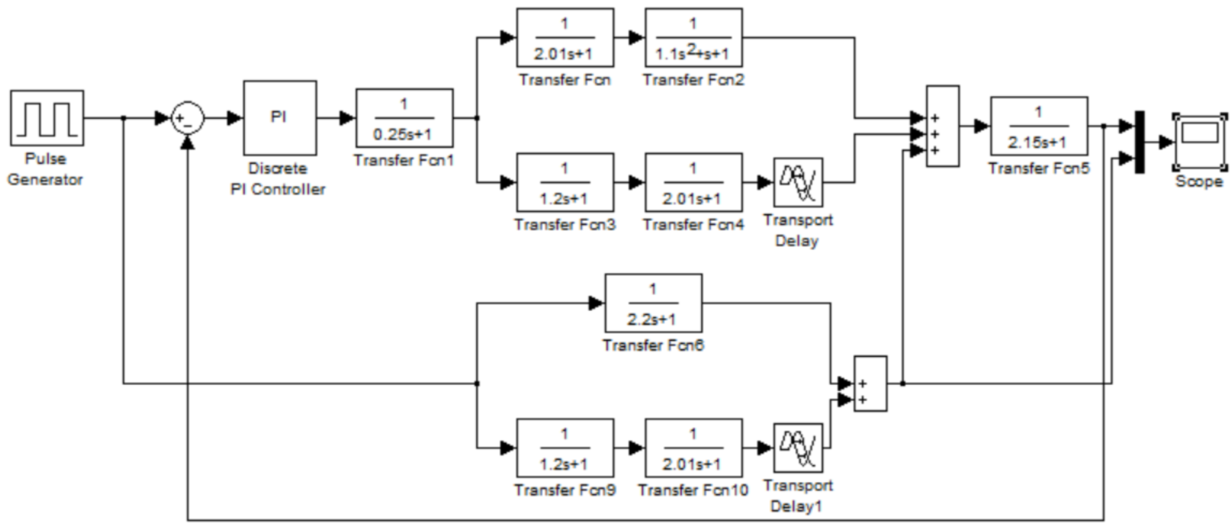

FIGURE 5. Structural scheme of the system for adjusting the pressure in the process of natural gas absorption purification based on the reference model.

A single-loop PI regulator is used for the system for adjusting the pressure of hydrocarbon condensate in a multi-plate absorption column. The coefficients of the PI regulator are calculated using the selected control algorithm. Requirements are set for these coefficients to ensure the quality of adjustment of the transition characteristic of the output parameter of the natural gas pressure inside the structure. The MATLAB 6.1 (Simulink) program performs the structural scheme of the system and calculations $K_P = 0.4$ and $K_I = 0.1$.

In Figure 9, the initial step signal given by the control object is connected directly to the “Scope” block. In order to assess the quality of the installed PID controller, the transition characteristics are built in one place.

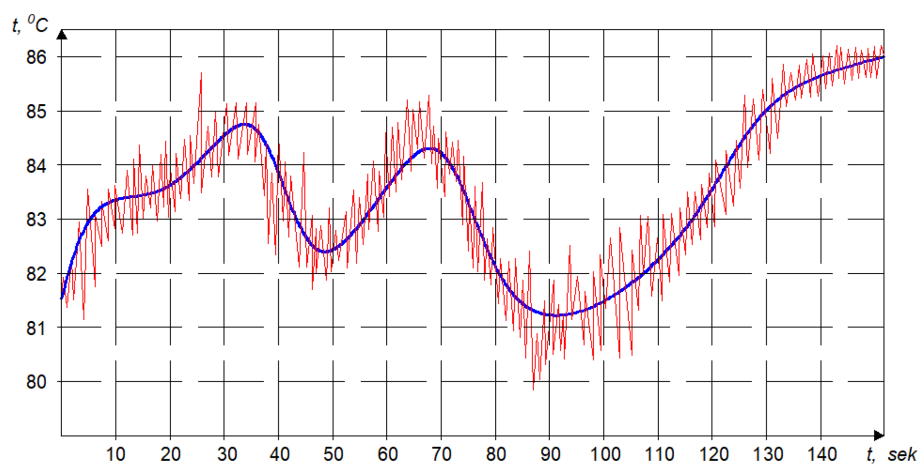

FIGURE 6. Transition characteristics of adjusting the natural gas pressure in the absorption column using a regulator based on the reference model.

In the technological process of natural gas purification by absorption, the output parameters are the temperature of natural gas condensate and water vapor. As additional output parameters, the change in condensate and gas pressure in the structure is taken. In the graph above, the red line represents the natural gas temperature by time transition characteristic. The blue line is the natural gas temperature by time transition characteristic for the control system based on the reference model.

CONCLUSION

The stages of synthesizing adaptive control systems based on the reference model for technological plants were analyzed. The practice of determining the coefficients of the transfer function in adaptive control systems was carried out. Structural analysis was performed in synthesizing adaptive control systems based on the reference model for technological plants. The control system based on the reference model was synthesized in controlling the parameters of the technological process of natural gas purification by absorption, and certain results were obtained.

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