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SYNTHESIS OF A CONTROL SYSTEM FOR A NON-STATIONARY DYNAMIC PLANT BASED ON A REGULATOR-PREDICTOR

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Abstract: *The paper considers the issues of synthesizing a predictor controller as part of a control system for a non-stationary dynamic plant with a predictive model. Technological processes in industry, in essence, have non-stationarity properties, the parameters of which can change during the execution of technological operations. To control such nonstationary dynamic control plants, controllers built on the basis of predictive models have found wide application. The article is devoted to the issue of studying automatic control systems of a non-stationary dynamic plant with a base regulator-predictor. To synthesize a regulator - predictor, it is proposed to use a predictive model of a non-stationary plant, which makes it possible to ensure the best trajectory of the controlled variable feature of using the regulator – predictor the presence of an accurate model of the plant. A mathematical model of the impregnation reservoir has been developed in an analytical method using material balance controls. To determine the value of optimal control actions, the least squares method was used. To check the reliability of the proposed methodology, a simulation experiment was carried out, changing the parameters of the control plant to produce a harmonic effect with a certain amplitude and frequency. Based on the obtained transient processes, the quality indicators of the control system were determined. Comparative and analysis of the results obtained allowed us to draw a conclusion about the advantages of the proposed regulator-predictor over others.*
Keywords: *control system, regulator-predictor, predictive model, non-stationarity, dynamics, synthesis, optimization.*

Annotatsiya: *Maqolada bashoratlovhi-rostlagichni bashoratli model bilan statsionar bo'lmagan dinamik obyektni boshqarish tizimining bir qismi sifatida sintezlash masalalari ko'rib chiqilgan. Sanoatdagi texnologik jarayonlar mohiyatan statsionar bo'lmagan xususiyatlarga ega bo'lib, ularning parametrlari texnologik amallar davomida o'zgarishi mumkin. Bunday nostatsionar dinamik boshqarish obyektlarini boshqarish uchun bashoratli modellar tomonidan qurilgan rostlagichlar keng qo'llaniladi. Maqola statsionar bo'lmagan dinamik obyektni bashoratlovchi-rostlagichga asoslangan avtomatik boshqarish tizimlarini o'rganish masalasiga bag'ishlangan. Bashoratli-rostlagichni sintez lash uchun statsionar bo'lmagan obyektning bashoratli modelidan foydalanish taklif etilgan, bu esa bashorat qiluvchi rostlagichdan foydalanishning nazorat qilinadigan o'zgaruvchan xususiyatining eng yaxshi traektoriyasini - obyektning aniq modeli mavjudligini ta'minlash imkonini beradi. Moddiy balansni boshqarish vositalaridan foydalangan holda analitik usulda singdirish vannasining matematik modeli ishlab chiqilgan. Optimal boshqarish ta'sirlarining qiymatini aniqlash uchun eng kichik kvadratlar usuli qo'llanilgan. Taklif etilgan usulning ishonchliligini tekshirish uchun ma'lum bir amplituda va chastota bilan garmonik ta'sir hosil qilish uchun boshqarish obyektining parametrlarini o'zgartirgan holda imitatsion tajribasi o'tkazilgan. Olingan o'tkinchi jarayonlar asosida boshqarish tizimining sifat ko'rsatkichlari aniqlangan. Olingan natijalarni taqqoslash va tahlil qilish bashorat qiluvchi rostlagichlarning boshqasidan ustunligi haqida xulosa chiqarish imkonini beradi.*
Tayanch so'zlar: *boshqarish tizimi, bashoratlovchi-rostlagich, bashorat qiluvchi model, nostatsionarlik, dinamika, sintez, optimallashtirish.*

Аннотация: *В работе рассматриваются вопросы синтеза регулятора-предсказателя в составе системы управления нестационарным динамическим объектом с прогнозирующей моделью. Технологические процессы в* *промышленности, по существу, имеют свойства нестационарности, параметры которых могут изменяться в течения выполнения технологических операций. Для управления подобными нестационарными динамическими объектами управления широкое применение нашли регуляторы, построенные на базе прогнозирующих моделей. Статья посвящена вопросу исследования систем автоматического управления нестационарным динамическим объектом с базой регулятором- предсказателем. Для синтеза регулятора-предсказателя предложено использование прогнозирующая модель нестационарного объекта, позволяющая обеспечить наилучшая траектория контролируемой переменной особенностью применения регулятора-предиктора наличие точной модели объекта. Разработана математическая модель пропиточной ванны, аналитическим способом, используя управления материального баланса. Для определения значения оптимальных управляющих воздействий применен метод наименьших квадратов. Для проверки достоверности предложенной методики проводился имитационный эксперимент, изменялись параметры объекта управлении, подавались гармоническое воздействие с определенной амплитудой и частоты. На основе данных были полученных переходные процессов, для определены показателя качества системы управление. Анализ полученным результатов позволили сделать заключение о преимуществах предложенной регулятора-предсказателя перед другим.*

***Ключевые слова**: система управление, регулятор-предиктор, прогнозирующая модель, не-стационарность, динамика, синтез, оптимизация.*

Introduction

Currently, automatic control systems are widely used in industry, the use of which is due to the need to improve the quality of the technological process, as well as to improve the quality indicators of the control system as a whole [1,2]. It is known that most technological objects operating in industry are non-stationary causes control plants. Non-stationarity is the change of dynamic properties and order of the dynamic model of the plant in real time. It is known that control of such plants using traditional classical PID controllers does not provide the control system with the desired properties [1,3,4].

The first method improving the goodness of automatic control systems for non-stationary control plants is to combine a standard PID controller with a fuzzy adaptive controller. The fuzzy controller is most often tuned on the basis of the Mamdani controller [5].

Also, recently, controllers built on the basis of a predictive regulator-predictor model have been widely used to control non-stationary dynamic plants. To synthesize such a controller, it is necessary to have an accurate mathematical model of the control plant, on the basis of which the controller predicts the change in the controlled variable for a certain period of time in advance and determines the effective quantity of the control signal to ensure the best trajectory of the variables controlled [4,6].

Research Methods and the Received Results

The paper discusses the issues of synthesizing an automatic control system for a non-stationary dynamic plant, the parameters of which can change during the technological process of its operation.

We will consider the dynamics of the control plant both through the control channel and through the disturbance channel. The dynamics of the control plant is described by the transfer function $W_0^u(p)$ for control and the transfer function $W_0^f(p)$ for disturbance:

$$\begin{aligned} W_0^u(p) &= \frac{k}{T\,p+1}\cdot e^{-\tau\,p}, \\ W_0^f(p) &= \frac{k^f}{T^f\,p+1}\cdot e^{-\tau^f p}. \end{aligned} \tag{1}$$

During the technological process, when the operating mode of the plant changes and when the dynamic characteristics of the processed material change, the blocks of the transfer function defining the control plant along the control channel $W^u(p)$ can change. In the case under consideration, the alters of the control plant will be defined by the given transfer functions:

$$W^u(p) = \frac{k}{(T_1 p+1)\cdot(T_2 p+1)\cdot(T_3 p+1)\cdot}\cdot e^{-\tau\, p},$$
$$W^f(p) = \frac{k^f}{T^f p+1}\cdot e^{-\tau^f p}. \qquad (2)$$

As an example, let us consider the technological process of whitening of fabrics in the textile industry. The process of bleaching is a chemical process and occurs as follows. There are two reservoirs, one of which contains water at a temperature of 20-40 °C, the other contains a dosed liquid, mainly a solution of caustic soda and hydrogen peroxide ($NaOH + H_2O_2$).

Additionally, altering the parameters and dynamic properties of the control plant, stepwise disturbances of unknown amplitude and duration also operate during the technological process.

The diagram of the proposed system for automatic control of the bleaching process with a predictor regulator is shown in Fig. 1. The proposed control system was implemented in the MATLAB/Simulink package. A predictor-regulator was synthesized using the MPC Toolbox software tool.

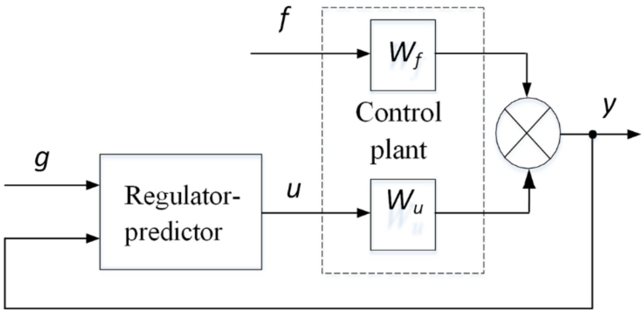

Fig. 1. ***Controlling system based on regulator-predictor.***

The structural diagram of the implemented regulator-predictor is shown in Fig. 2. The regulator includes: a predictive model and an optimization block[6,7,8,9].

The essence of a control system with a predictive model is as follows: a control signal $u(t)$ is supplied to the input of the plant, and the controlled variable $y(t)$ is measured at the output, while $g(t)$ is the desired characteristics of regulated parameters. Since a microcontroller is used as a control device, we will consider only at moments of time $t = k{\cdot}\Delta T$, while ΔT - is the period of pulse construction, and k - is some integer.

The main feature of technological process control using a regulator-predictor is the presence of an accurate mathematical model of the control plant.

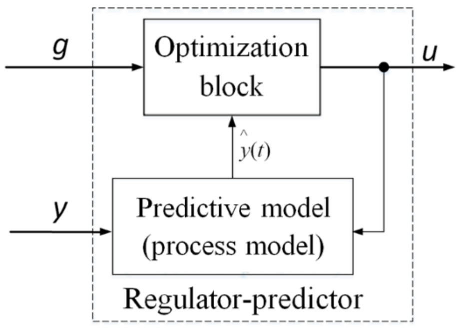

Fig. 2. ***Structural scheme of the regulator-predictor.***

For this purpose, using the equations of material balance describing the dynamics of the impregnation reservoir [2,10]:

$$\frac{dm}{dt} = \sum_{i=1}^{n} M_{ei} - \sum_{j=1}^{k} M_{aj}\ , \tag{3}$$

where m - is the mass contained in a given volume; M_{ei} and M_{aj} - are flows of matter entering and leaving a given plant.

The initial conditions in the impregnation reservoir are: $V_o = 0.6m^3$; $c_p = 220\,kg/m^3$; $c_{p0} = 30kg/m^3$; $q_1 = 1,0$; $q_2 = 1,2$; $p_1 \approx p_2 \approx 1000kg/m^3$; $x = 1.1$; $m = 0.104кг$; $Q_n = 2,4l/min = 0,04*10^{-3}m^3/s.$ speed of fabric movement $v = 80m/min = 1,33m/s.$ It is necessary to obtain $c_p = 20kg/m^3.$ In order to establish this concentration, it is necessary to supply water to the reservoir in an amount $Q_в \approx 60l/min = 1\ *10^{-3}m^3/s$.

The reservoir receives fabric impregnated in water or solution and wrung out in the previous machine. Let's introduce the concept of fabric mass speed (kg/s)

$$M = \mu v = 0{,}104*1.33 = 0.138(кг/с),$$

where μ- is the mass of a piece of dry fabric 1 m long (*kg/m*); V - is the speed of movement of the fabric in the machine (*m/s*).

The extraction of fabric in squeezing devices is characterized by the value

$$q = \frac{M_{pres}}{\mu} = \frac{M_{pres}}{M}, \tag{4}$$

where M_{pres} - is the mass of the pressed fabric (here the spin q is expressed in fractions, often it is expressed as a percentage).

Because,

$$\mu_{pres} = \mu + Lp,$$

where L - is the volume of liquid contained in a meter piece of wrung out fabric, ***p*** - is the density of this liquid, then $M_{pres} - M + L_p$ and the amount of liquid carried away by the fabric after wrung out (***m/s***) is equal to:

$$vL = q\frac{M}{p} = 1.1\ *(0.138/1000). \tag{5}$$

At a constant reservoir volume ***V***, which is achieved by regulating the level by adding water in the amount of $Q_B(m^3/s)$, the liquid balance equation in the reservoir will take the form:

$$Q_n + Q_B + q_1\frac{M}{p_1} = q_2\frac{M}{p_2}\text{, that is} \tag{6}$$

$$0.04*10^{-3} + 1*10^{-3} + 0.138/1000 = (1.2*1.138)/1000,$$

where q_1 - is the spin of the previous machine; p_1 - is the density of the solution in it; q_2 - spinning the fabric after impregnation in the reservoir; p_2 - is the density of the solution in the reservoir. Equation of material balance of a chemical reagent in a reservoir at steady state and at k=0

$$Q_n c_n = xq_2\frac{M}{p_2}c_p \text{ т.е.} \quad 0.04*10^{-3}*220 = (1.1*1.2*0.104*30)/1000. \tag{7}$$

Here c_p - concentration of the chemical reagent in the reservoir (kg/m^3).

In unsteady operating conditions we have:

$$\left[Q_n c_n + \Delta(Q_n c_n) - xq_2\frac{M}{p_2}c_p - \Delta(xq_2\frac{M}{p_2}c_p)\right]\Delta t = V\Delta c_p$$

Passing to the limit at $\Delta t \to 0$ and taking into account (7), we obtain:

$$V\frac{d\Delta c_p}{dt} = \Delta(Q_n c_n) - \Delta(xq_2\frac{M}{p_2}c_p) \tag{8}$$

The terms on the right side of equation (8) are equal to:

$$\Delta(Q_n c_n) = (\frac{\partial}{\partial c_n} Q_n c_n)_0 \Delta c_n = c_{n,o}\Delta Q_n + Q_{n,o}\Delta c_n;$$

$$\Delta(xq_2 \frac{M}{p_2} c_p) = (\frac{\partial}{\partial c_n} xq_2 \frac{M}{p_2} c_p)\Delta c_p + (\frac{\partial}{\partial q_2} xq_2 \frac{M}{p_2} c_p)\Delta q_2 + (\frac{\partial}{\partial M} xq_2 \frac{M}{p_2} c_p)\Delta M =$$

$$= xq_{2,0} \frac{M}{p_2} c_p + x\frac{M_0}{p_2} c_{p,0}\Delta q_2 + xq_{2,0}\frac{c_{p,0}}{p_2}\Delta M$$

Here the index zero has values characterizing the average steady state. Substituting the value into equation (7) and transforming them we get:

$$\frac{d\Delta c_p}{dt} + xq_{2,0}\frac{M_0}{Vp_2} c_{p,0}\Delta c_p = \frac{c_{n,0}}{V}\Delta Q_n + \frac{Q_{n,0}}{V}\Delta c_n - x\frac{M_0}{Vp_2} c_{p,0}\Delta q_2 - xq_{2,0}\frac{c_{p,0}}{Vp_2}\Delta M \tag{9}$$

When a chemical reagent decomposes in a reservoir, i.e. at $k \neq 1$, equation (8) is transformed into the equation:

$$\frac{d\Delta c_p}{dt} + \frac{xq_{2,0}M_0 + Vkp_2}{Vp_2}\Delta c_p = \frac{c_{n,0}}{V}\Delta Q_n + \frac{Q_{n,0}}{V}\Delta c_n - x\frac{M_0 c_{p,0}}{Vp_2}\Delta q_2 - xq_{2,0}\frac{c_{p,0}}{Vp_2}\Delta M \tag{10}$$

The dynamics of changes of the concentration are described in Equation (8) and its solution in the reservoir in the presence of disturbances caused by changes in the influx of the feeding solution ΔQ_n, its concentration Δc_n, spin Δq_2 and mass velocity of the tissue ΔM.

If there are no disturbances, i.e. $\Delta Q_n = \Delta c_n = \Delta q_2 = \Delta M = 0$, then taking into account the fact that

$$\Delta c_p = c_t - c_0$$

where c_0 – is the initial concentration, and c_t - is the concentration at time ***t***, equation (8) will be written as:

$$\frac{dc_{t1}}{dt} + xq_{2,0}\frac{M_0}{Vp_2}c_1 = xq_{2,0}\frac{M_0}{Vp_2}c_0$$ or taking into account equation (6),

$$\frac{dc_t}{dt} + xq_{2,0}\frac{M_0}{Vp_2}c_1 = \frac{Q_{n,0}c_{n,0}}{V} \tag{11}$$

When a chemical reagent decomposes in a reservoir , i.e. at $k \neq 1$, equation (11) transforms into equation

$$\frac{dc_t}{dt} + \frac{xq_{2,0}M_0 + Vkp_2}{Vp_2} = \frac{Q_{n,0}c_{n,0}}{V} \tag{12}$$

Solution of this equation under initial conditions $t=0$, $c_t=c_0$

$$c_t = (c_0 - c_{n,0}\frac{Q_{n,0}p_2}{xq_{2,0}M_0 + Vkp_2})e^{\frac{xq_{2,0}M_0+Vkp_2}{Vkp_2}} + \frac{Q_{n,0}p_2}{xq_{2,0}M_0 + Vkp_2} \tag{13}$$

The second term of the equation gives the steady-state concentration value in a given operating mode

$$c_{уст} = \lim_{t\to 0} c_t = c_{n,0}\frac{Q_{n,0}p_2}{xq_{2,0}M_0 + Vkp_2} = 220\frac{0.000165*1000}{1.1*1.2*0.138 + 0.6*1000} = 199.4 \tag{14}$$

When dry fabric enters the reservoir, the influx of feeding solution is equal to the volume of liquid carried away by the wrung out fabric, i.e. $Q_{n,0} = \frac{q_{2,0}}{p_2} = \frac{1.2*0.138}{1000} = 0.000165$, and the steady-state concentration in this case is equal to:

$$c_{st} = c_{n,0}\frac{Q_{n,0}p_2}{xq_{2,0}M_0 + Vkp_2} = c_{n,0}\frac{Q_{n,0}}{M_{n,0} + Vk}$$

If the concentration is controlled by measuring the concentration c_p and the corresponding change in the inflow of the feeding solution Q_n, then the properties of the reservoir as a control plant are characterized by equation (7), which after transformation is reduced to the following form:

$$\frac{Vkp_2}{xq_{2,0}M_0+Vkp_2}\frac{d\Delta c_p}{dt}+\Delta c_p=\frac{c_{n,0}p_2}{xq_{2,0}M_0+Vkp_2}\Delta Q_n+\frac{Q_{n,0}p_2}{xq_{2,0}M_0+Vkp_2}\Delta c_n-\frac{xM_0c_{p,0}}{xq_{2,0}M_0+Vkp_2}\Delta q_2- \\ -\frac{xq_{2,0}c_{p,0}}{xq_{2,0}M_0+Vkp_2}\Delta M \quad (15)$$

To move to dimensionless quantities, we introduce the following notation: $\varphi=\frac{\Delta c_p}{c_{p,0}}$ - - relative change in the concentration of the solution in the reservoir; $\mu=\frac{\Delta Qn}{Q_{n,\max}}$ - relative change in the inflow of solution (regulatory effect); $f_1=\frac{\Delta c_n}{c_{n,0}}$ - relative change in the concentration of the feeding solution; $f_2=\frac{\Delta q_2}{q_{2,0}}$ - relative change in spin; $f_3=\frac{\Delta M}{M_0}$ - relative change in tissue mass velocity.

Using this notation, equation (15) becomes:

$$\frac{Vkp_2}{xq_{2,0}M_0+Vkp_2}\frac{d\varphi}{dt}+\varphi=\frac{Q_{n,\text{макс}}p_2}{xq_{2,0}M_0+Vkp_2}\frac{c_{n,0}}{c_{p,0}}\mu+\frac{Q_{n,0}p_2}{xq_{2,0}M_0+Vkp_2}\frac{c_{n,0}}{c_{p,0}}f_1- \\ -\frac{xq_{2,0}M_0}{xq_{2,0}M_0+Vkp_2}f_2-\frac{xq_{2,0}M_0}{xq_{2,0}M_0+Vkp_2}f_3 \quad (16)$$

or

$$T_0\frac{d\varphi}{dt}+\varphi=K_0\mu+K_1f_1-K_2f_2-K_3f_3$$

Thus, in its dynamic properties, the reservoir is, to a first approximation, similar to a first-order aperiodic link with a time constant

$$T=\frac{Vkp_2}{xq_{2,0}M_0+Vkp_2}=\frac{0.6*100}{1.1*1.2*0.138}=3296c\approx 3300c$$

Transfer function of the plant in relation to the regulatory influence

$$W_0(p)=\frac{K_0}{T_0p+1},$$

where $K=\frac{Q_{n,\text{макс}}p_2}{xq_{2,0}M_0+Vkp_2}\frac{c_{n,0}}{c_{p,0}}=\frac{0.04*10^{-3}*1000}{1.1*1.2*0.138}\frac{220}{30}=\frac{8800*10^{-3}}{5.46}=1.61.$

The transfer functions of the plant in relation to each of the disturbances have the same form, but they differ only in the value of the transfer coefficients K_1, K_2, K_3.

It is known that the impregnation reservoir is an plant with distributed parameters, since the feed solution and water are supplied unevenly throughout the entire volume of the bath, and therefore the spread of the solution with a changed concentration throughout the entire volume of the bath occurs at a certain final speed. This leads to a delay and the transfer function of the plant takes the following form.

$$W_0(p)=\frac{K_0}{T_0p+1}e^{-p\tau} \ ,$$

where τ - is the delay time .

The value of τ can be determined experimentally (by taking the acceleration curve of a specific reservoir).

In an unsteady mode (with a variable volume of solution in the reservoir) that occurs during forcing, the change in the concentration of the solution in the reservoir over time ***t*** at $k=0$ is equal to:

$$\Delta c_p(t)=c_p(t)-c_{p,0}=\left(\frac{Q_nc_n}{xq_2\frac{M}{p_{2\,0}}+\Delta Q}-c_{p,0}\right)\times\left[1-(1+\frac{\Delta Q}{V_0}t)^{-\frac{xq_2\frac{M}{p_{2\,0}}+\Delta Q}{\Delta Q}}\right]=$$

$$=-30\left[1-\left(1+\frac{1.10^{-3}}{0.6}120\right)^{-\frac{1.1*1.2\frac{0.138}{1000}+1*10^{-3}}{1*10^{-3}}}\right]=-30(1-1.2^{-1.183})=-6\ kg/m^3,$$

where $c_{p,0}$ - is the concentration of the solution at the start of forcing; $c_p(t)$ - concentration after time ***t*** after the start of forcing.

It follows that the time to establish a given concentration will be equal to:

$$-6=-30(1-e^{\frac{-t}{3300}});\quad e\frac{-t}{3300}=0.8;\qquad t=12\ min.;\quad t=(3.5)T_{pl};\quad T_1=12/5=2,4*60=144s.$$

Similarly, using the obtained equations based on the material balance equation, we find the following values:

$$T_2=280;\quad T_3=138;\quad T_4=161;\quad K_1=1,61;\quad K_2=0,8;\quad K_3=1,2;\quad K_4=2.$$

At a certain number of following steps, the presence of an adequate mathematical equations of the control plant creates chance one to predict the quantity of the controlled variable (Fig. 3).

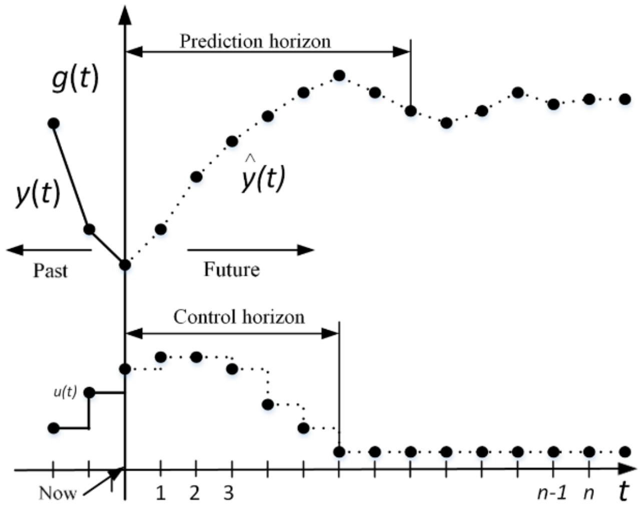

Fig. 3. ***Graphs of controlling process using a regulator-predictor.***

$y(t)$ - the quantity of the regulated parameters of liquid concentration in the reservoir, predicted at the moment on *t*, in Fig. 3 are designated as $\hat{y}(t)$. Over a certain number of steps create the prediction horizon. The predicted trajectory of the controlled variable will depend on the values of the control signal *u(t).*

The essence of the method for synthesizing a control system is to determine the sequence of quantity of the control signal $u(t)$ that allow us to provide the best trajectory for the regulated parameters $y(t)$. The control horizon is the duration of control signals $u(t)$. The quantity of the control signal is calculated as a result of solving the optimization problem.

To solve the optimization problem, you can use the criterion of squared error between the predicted output parameters of the control plant $y(t)$ and the desired characteristics $g(t)$. As a functional, you can use a criterion described in the following form:

$$J=\sum_{i=l}^{l+he}\left(g(i)-y(i)\right)^2+\sum_{i=l}^{l+hu}\left(u(i)-u(l)\right)^2, \qquad (17)$$

where l = 1, 2, …, ∞; *he* – he – the number of control cycles for which the behavior of the regulated parameters $y(t)$ is predicted; *hu* – is the duration of the control action values $u(t)$.

Using the least squares method [19,20], we determine the required values of control actions for each control cycle.

Fig. 4 shows the functioning algorithm of the regulator-predictor.

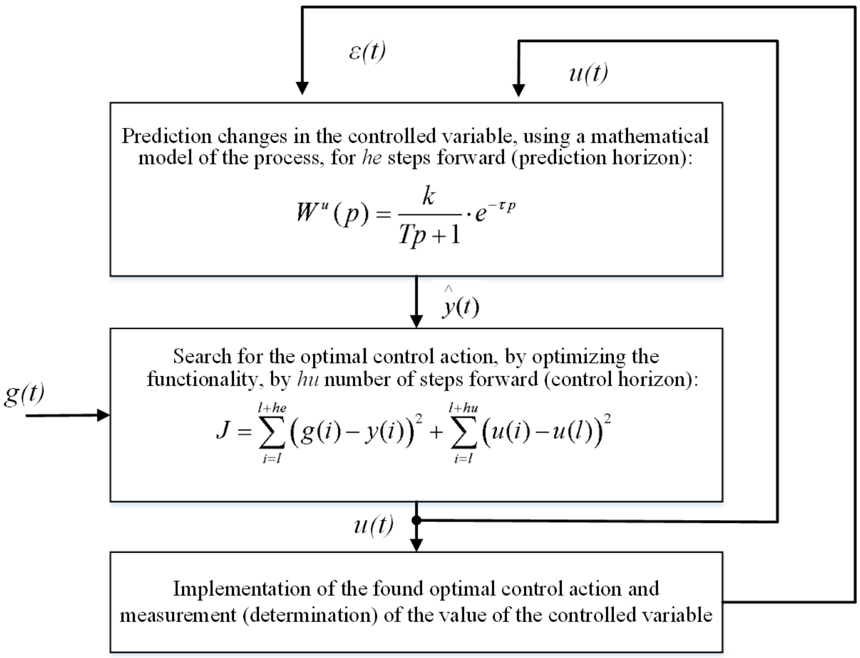

Fig. 4. ***Algorithm for the functioning of the regulator-predictor.***

To synthesize a regulator-predictor, consider a control plant whose transfer function is presented in (1), the automatic control system was subject to a restriction on the control signal.

The desired quantity for the regulated parameters-controlled variable is set (set-point Y=50%). Fig. 5. shows the transient processes gained as a result of the reference influence.

Seeing the transition process characteristics (Fig. 5), clearly the controls bring the regulated parameters to the specified level. In this case, the regulation time of the automatic control system with a regulator-predictor is 33 s. There is no overshoot of the automatic control system. For the obtained transient processes, the quadratic integral criterion (***J***) of the quality of transient processes was calculated using the given equation:

$$J = \int_{t_1}^{t_2} \left(g(t) - y(t)\right)^2 dt. \tag{18}$$

Having analyzed the obtained quality indicators, we note that the best transient process for the reference action is provided by an automatic control system with a regulator-predictor [19].

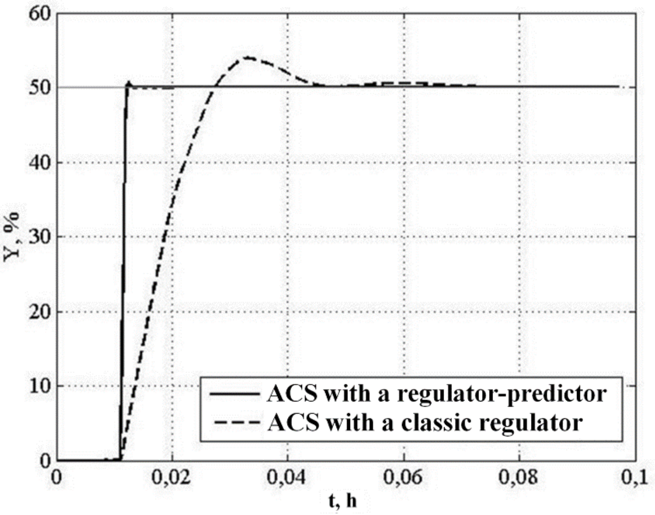

Fig. 5. ***Transient processes according to the reference influence.***

Conclusion

This research is devoted to the synthesis of automatic control systems with the proposed regulator-predictor. The features, both superiority and no superiority of the considered regulator-predictor are given.

When given the controlled variable to a given level, the best indicators of the quality of transient processes were shown by a control system with a regulator-predictor. When using a regulator-predictor, the control time is 3.7 times less than with classic PID controllers

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