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SYNTHESIS OF ROBUST CONTROLLER WITH AN INTERNAL MODEL FOR OBJECTS WITHOUT SELF-ALIGNMENT

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Розглянуті особливості проектування робастних систем керування на базі H_∞-норми замкненої системи з об'єктом без самовирівнювання. Запропонована методика синтезу робастного регулятора для інтегральних об'єктів 1-го і 2-го порядку. Встановлено однозначні залежності між параметром налаштування робастного регулятора та основними показниками якості функціонування системи керування. Отримана методика синтезу дозволяє швидко і однозначно налаштувати регулятор для об'єкту без самовирівнювання на задані показники якості

***Ключові слова:** синтез регулятора, внутрішня модель, H_∞-норма, інтегральний об'єкт, показники якості*

Рассмотрены особенности проектирования робастных систем управления на базе H_∞-нормы замкнутой системы с объектом без самовыравнивания. Предложена методика синтеза робастного регулятора для интегральных объектов 1-го и 2-го порядка. Установлены однозначные зависимости между параметром настройки робастного регулятора и основными показателями качества функционирования системы управления. Полученная методика синтеза позволяет быстро и однозначно настроить регулятор для объекта без самовыравнивания на заданные показатели качества

***Ключевые слова:** синтез регулятора, внутренняя модель, H_∞-норма, интегральный объект, показатели качества*

1. Introduction

Ensuring reliable operation of the equipment of energy units is achieved by maintaining its basic parameters and, in some cases, by the speed of replacement in quite a narrow range. Therefore, stable operation of the equipment requires expanding the functions of automated control systems (ACS) putting forward strict requirements to the quality of their work.

Application of robust approach makes it possible to considerably simplify the hardware and software employed in ACS, because the possibility of a priori choice of the structure and parameters of controllers reduces the cost of adjusting and maintenance of the system [1]. The main feature of the H -controllers is that in the process of functioning of the robust system, only a priori information is used about possible external disturbance [2]. This leads to the fact that the robust systems are characterized by certain conservatism, that is, such controller is always prepared for the worst case.

Rigorous mathematical methods of the robust synthesis, however, are not absolutely suitable for solving specific engineering tasks. This is predetermined by the large complexity of the applied computing procedures, high order of the received controllers and unsuitability of these methods for the objects with delay. Under such situation, it is a very promising task to develop simple methods for the synthesis of robust systems.

Control system's operation quality depends both on the controller and the type of object. In most cases, controller is designed taking into account specificity of the control object. If the system controls an object without self-alignment, the achievement of acceptable control quality is much more complicated. The main feature of the object without self-alignment is that its model contains the integrators, which is a specific feature of unstable objects. For the stable objects, there were developed many control strategies, such as PID controller or the Smith predictor. At the same time, a quantity of such methods is much less for integral objects [3]. Though the PID controller can be used in order to control integral objects, but this often leads to a deterioration in the quality of control. For the Smith predictor, a closed system is internally unstable since the object itself is not stable.

Thus, development of the controller, which possesses robust properties and can be configured to direct quality indicators that are clear to actual users is a relevant task that makes it possible to expand the scope of its application to the objects without self-alignment.

2. Literature review and problem statement

The existence of possibility for accurate identification of the control object makes it possible to avoid a procedure of sophisticated adjustment of control system once a controller with internal model is employed. This idea is a starting point for the principle, which is called Internal Model Control (IMC), since the object model is an implicit internal part of the controller [4].

The principle of control using an internal model is based on the assumption that the control is effective when the system to some extent incorporates the features of the object that it controls. That is, if the control unit includes an object model, it is theoretically possible to attain a perfect quality of control (absence of re-regulation, process variability, minimal time for regulation).

The essence of such an approach is that the identification of the object model and the introduction of controller to the structure will lead to a high-quality response to a change in the task, enabling efficient reaction to external disturbances.

Article [5] considered the most often used integral quality indicators, direct indicators of the transient processes quality over temporal and frequency regions and the conditions for robust stability. A modified IMC synthesis was proposed in order to improve transition processes by the channel external disturbances – output for objects with large time constants. The main idea of the given method is to reduce the respective poles of characteristic equation. The formulae were analytically derived for adjusting the controllers, along with conditions for robust stability.

Ideas that are explored in the robust control theory were eventually applied also for the PID control. Such penetration gave rise to the methods that are called robust PID-control [6]. In this case, there is a distinction in terms of receiving a robust PID controller, which is the result of solving a problem on the robust control for a limited structure of the controller. Because setting the PI- and PID-controllers is most commonly used in practice, the methods were given for PID adjustment based on the IMC synthesis.

The examined methods include explicit consideration of robustness in its principle. One can highlight two common approaches among them. The first one includes methods under which a robust control system is obtained, but it is not bound by any indicator of robustness [7]. There are deeper methods for setting up the PID controllers based on the IMC synthesis, in order to improve transition processes by the channel disturbance-output, which were proposed in [8]. According to second approach, the explicit terms and definitions of robustness are used, in order to achieve robustness desired for a closed system. Thus, [9] employs a comprehensive frequency indicator – the maximum of a sensitivity function. Studies in this direction have been expanded to cover the systems with two degrees of freedom [10].

As a result of employing the H_∞-norm of a closed system as a criterion of optimality, [11] obtained setting a PID controller for objects with delay. It is proved that by changing a parameter of adjusting the controller, it is possible to attain the desired trade-off between the required quality indicators of the system and the robustness. H_∞-norm of the closed system as an optimality criterion enables simple and quick setting of a PID controller for the objects of first and second orders with delay. These studies were extended in [12], which outlined the benefits of applying a controller with such a structure. Paper [13] reported comparative studies into standard PI-controllers and the new structures of robust controllers. Article [14] obtained the structures of the controller with internal model based on the H_∞-norm for systems with two degrees of freedom.

However, all the above studies are related only to the objects with self-alignment. The need to embrace the possibility of applying such a control structure for the objects that include an integral component predetermine the need for continued research in this direction.

3. Research goal and objectives

The goal of present work is to build an H_∞-controller with internal model for the objects without self-alignment and to study techniques for its adjustment.

To accomplish the set goal, the following tasks have been resolved:

– to receive a structure of the controller with internal model for the objects without self-alignment based on the H_∞-norm of a closed system;

– to determine the impact of parameters of the H_∞-IMC-controller on the basic quality indicators of ACS operation;

– to create a program for the selection of settings of H_∞-controller, which would guarantee to provide a robust system with a desired quality indicator or a combination.

4. Materials and methods to study the IMC-H_∞-controller for objects without self-alignment

The minimum requirement to a control system is the internal stability. Let us consider control system with a feedback shown in Fig. 1, where P is the object without self-alignment, R is the controller.

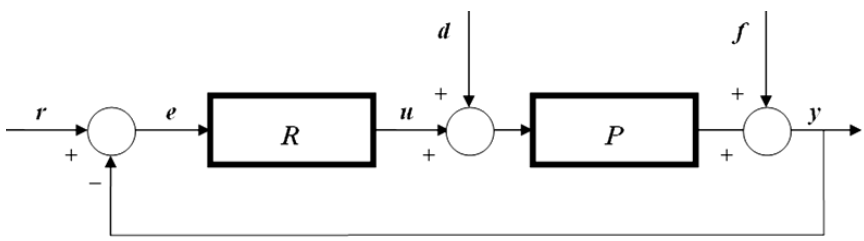

Fig. 1. Control system with a feedback

Such system has two independent outputs and two independent inputs. It is possible to select $r(s)$ and $d(s)$ as inputs, and $y(s)$ and $u(s)$ as outputs. A closed system is internally stable when and only when if all the elements of the transfer function of matrix $H(s)$ from $r(s)$ and $d(s)$ to $y(s)$ and $u(s)$ are stable:

$$\begin{bmatrix} y(s) \\ u(s) \end{bmatrix} = H(s) \begin{bmatrix} r(s) \\ d(s) \end{bmatrix}, \quad (1)$$

where

$$H(s) = \begin{bmatrix} \dfrac{P(s)R(s)}{1+P(s)R(s)} & \dfrac{P(s)}{1+P(s)R(s)} \\ \dfrac{R(s)}{1+P(s)R(s)} & \dfrac{-P(s)R(s)}{1+P(s)R(s)} \end{bmatrix}. \quad (2)$$

We shall consider now a structure with the IMC-controller, reduced to the classic form.

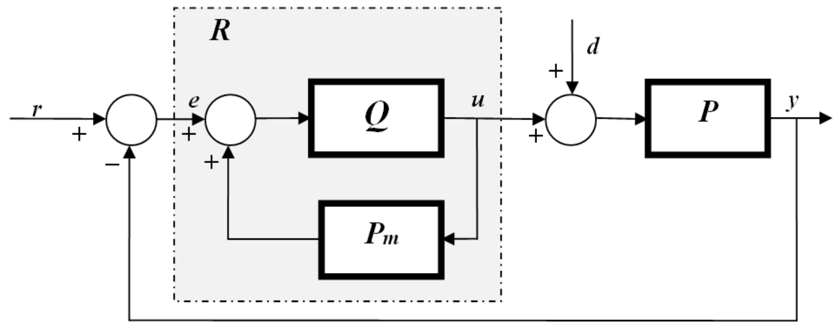

Fig. 2. System with the IMC-controller reduced to a classic form

Structure Q is called the IMC-controller. If P_m is considered as a reference control model, it can be built into the structure of the controller. Assume that the model is precise, that is, $P_m=P$. Then Q is determined in the form of the following transfer function:

$$Q(s)=\frac{R(s)}{1+P(s)R(s)}. \tag{3}$$

Therefore, a transfer function of the controller can be represented as

$$R(s)=\frac{Q(s)}{1-P(s)Q(s)}. \tag{4}$$

We shall rewrite matrix $H(s)$, defined in (2), in the form

$$H(s)=\begin{bmatrix} P(s)Q(s) & [1-P(s)Q(s)]P(s) \\ Q(s) & -P(s)Q(s) \end{bmatrix}. \tag{5}$$

In the case when object $P(s)$ is self-aligned, the system will be always internally stable whenever $Q(s)$ is stable. It is obvious that when object $P(s)$ possesses integral links, that is, it is not stable, then stability $Q(s)$ cannot guarantee stability of the closed-loop system.

Therefore, if $P(s)$ is an object without self-alignment, then the system shown in Fig. 2 is internally stable when and only when the two conditions are satisfied:

– $Q(s)$ is stable;

– $[1-P(s)Q(s)]\,P(s)$ is a stable transfer function.

General procedure of the synthesis, considered in [11], is as follows:

1) approximation of delay time by decomposition into a Taylor's or Padé series;

2) one chooses as an optimality criterion $\min \|V(s)S(s)\|_\infty$, where $V(s)$ is some function of weighting, which is selected depending on the input impact, and $S(s)$ is a sensitivity function;

3) deriving $Q_{opt}(s)$ by minimizing the optimality criterion;

4) calculation of controller $R(s)$ according to (4).

Let us consider an integral object (with self-alignment) of first order, which is described by the transfer function of the form:

$$P=\frac{K_o}{s}e^{-\tau s}. \tag{6}$$

Upon approximating the delay link by decomposing into a Padé series of first order, we receive:

$$P=\frac{K_o\left(1-s\,\tau/2\right)}{s\left(1+s\,\tau/2\right)}. \tag{7}$$

Internal stability requires

$$\lim_{s\to 0}\left[1-W_o(s)Q(s)\right]=0. \tag{8}$$

In order to satisfy this condition, $Q(s)$ should directly depend on s, and the free remainder should equal $1/K$, that is,

$$Q(s)=\frac{s\left[1+sQ_1(s)\right]}{K_o}, \tag{9}$$

where $Q_1(s)$ is the stable transfer function. Consider a stepwise disturbance as an input impact. Thus, the weighting function is determined as $V(s)=1/s$. Approximate model of the object has a zero at $2/\tau$. Hence, we obtain

$$\|V(s)S(s)\|_\infty=\|V(s)[1-P(s)Q(s)]\|_\infty\geq\left|V\left(2/\tau\right)\right|.$$

By minimizing a left part of the inequality, we receive

$$\min\left\|V(s)\left\{1-P(s)\frac{s\left[1+sQ_1(s)\right]}{K_o}\right\}\right\|_\infty=\frac{\tau}{2}. \tag{10}$$

Then optimal controller $Q_{1opt}(s)=\tau/2$.

Substituting this expression in (9) produces

$$Q_{opt}(s)=\frac{s}{K_o}\left(1+\frac{\tau}{2}s\right). \tag{11}$$

Similar to the objects with self-alignment, it is necessary to introduce filter $F(s)$, which performs several functions:

– optimal controller $Q_{opt}(s)$ is typically an improper fraction. That is why one of the main functions of the filter is to make $Q_{opt}(s)$ a proper fraction. Of course, the controller remains optimal even after the introduction of filter;

– since $S(s)=1-P(s)Q(s)$ and $T(s)=P(s)Q(s)$, then the filter settings can be used to adjust the nominal quality and stability, as well as for the quantitative compromise between these two goals;

– there is a direct link between a filter parameter and variable parameters of the object, since $u(s)=Q(s)r(s)$. If a control structure is not allowed to be modified, it is possible to confine with the variable control magnitude by adjusting the filter parameter.

In this case, the filter must satisfy the following minimal requirements:

– a closed system is internally stable;

– formula of the controller $Q(s)=Q_{opt}(s)F(s)$ is a proper fraction;

– asymptotic tracking is achieved.

Thus, the resulting controller $Q(s)$ is determined as: $Q(s)=Q_{opt}(s)F(s)$. For the asymptotic tracking, the system must meet the following condition:

$$\lim_{s\to 0}\frac{d^k}{ds^k}\left[1-P(s)Q(s)\right]=0,\quad k=0,1,\ldots, \tag{12}$$

or, which is equivalent,

$$\lim_{s\to 0}\frac{d}{ds}\left[1-P(s)Q(s)\right]=0. \qquad (13)$$

In order to achieve this, the filter should have a more complex form than in the system with a self-aligned object. In particular, it should include zero, that is, its overall structure is determined as:

$$F(s)=\frac{\beta s+1}{(\lambda s+1)^m}, \qquad (14)$$

where λ is the measure of quality, β is the positive real number that is chosen to satisfy (12). Coefficient m must be such that $Q(s)$ is properly defined, which is why it is selected according to the following formula:

$$m=\begin{cases}\deg\{num(Q_{opt})\}-\deg\{denom(Q_{opt})\}, & \text{if } \deg\{num(Q_{opt})\}>\deg\{denom(Q_{opt})\},\\ 1, & \text{if } \deg\{num(Q_{opt})\}=\deg\{denom(Q_{opt})\}.\end{cases}$$

It is obvious that the requirement of asymptotic tracking can be satisfied by the third order filter. Let us select such filter for the following structure:

$$F(s)=\frac{\left(3\lambda+\tau/2\right)s+1}{(\lambda s+1)^3}. \qquad (15)$$

Accordingly, the suboptimal controller will take the form

$$Q(s)=\frac{s(1+s\tau/2)\left[(3\lambda+\tau/2)s+1\right]}{K_o(\lambda s+1)^3}. \qquad (16)$$

Then the controller of the general system with a feedback will be derived as

$$R(s)=\frac{Q(s)}{1-P(s)Q(s)}=$$

$$=\frac{1}{K_o}\frac{\left(3\lambda\tau/2+\tau^2/4\right)s^2+(3\lambda+\tau)s+1}{\lambda^3 s^2+\left(3\lambda^2+3\lambda\tau/2+\tau^2/4\right)s}. \qquad (17)$$

Such structure through equivalent transforms can be reduced to a PID-controller:

$$R^{PID}(s)=k_r\left(1+\frac{1}{T_i s}+\frac{T_d s+1}{T_f s+1}\right), \qquad (18)$$

whose parameters will be determined by formulae

$$k_r=\frac{1}{K_o}\frac{3\lambda+\tau}{3\lambda^2+3\lambda\tau/2+\tau^2/4}, \qquad (19)$$

$$T_i=3\lambda+\tau,$$

$$T_d=\frac{3\lambda\tau/2+\tau^2/4}{3\lambda+\tau},$$

$$T_f=\frac{\lambda^3}{3\lambda^2+3\lambda\tau/2+\tau^2/4}.$$

Next, let us consider synthesis of the H_∞-IMC-controller for an object without self-alignment of second order, which can be described by the following transfer function:

$$P=\frac{K_o}{s(Ts+1)}e^{-\tau s}, \qquad (20)$$

where T is the time constant. By using the approximation of delay time by a Taylor's series of first order, function (20) can be represented as

$$P=\frac{K_o(1-\tau s)}{s(Ts+1)}. \qquad (21)$$

Using the above-described procedure of synthesis, we obtain optimal structure of the IMC-controller:

$$Q_{opt}=\frac{s(1+\tau s)}{K_o}. \qquad (22)$$

In order to receive an actual IMC-controller, a structure of the optimal one will be supplemented by a filter with the following settings

$$F=\frac{(3\lambda+\tau)s+1}{(\lambda s+1)^3}. \qquad (23)$$

According to (4), we obtain the structure of the controller

$$R=\frac{1}{K_o}\frac{(Ts+1)\left((3\lambda+\tau)s+1\right)}{\left(\lambda^3 s+3\lambda^2+3\lambda\tau+\tau^2\right)s}. \qquad (24)$$

The structure derived as(24) can also be reduced to a PID-controller in the form:

$$R^{PID}(s)=k_r\left(1+\frac{1}{T_i s}+T_d s\right)\frac{1}{T_f s+1}, \qquad (25)$$

whose parameters will be determined as

$$k_r=\frac{1}{K_o}\frac{3\lambda+\tau+T}{3\lambda^2+3\lambda\tau+\tau^2}, \qquad (26)$$

$$T_i=3\lambda+\tau+T,$$

$$T_d=\frac{(3\lambda+\tau)T}{3\lambda+\tau+T},$$

$$T_f=\frac{\lambda^3}{3\lambda^2+3\lambda\tau+\tau^2}.$$

Thus, the settings obtained for the H-IMC-controller can be applied for the automated control system, which includes in its composition an object without self-alignment and a PID-controller without changing a structure of the system itself.

5. Results of research into the impact of a setting parameter on the quality indicators during operation

It is important that the controller has only one adjustable parameter (λ), which is also the only time constant of the nominal transfer function of a closed system. In this case, λ is the parameter that is closely connected to the criteria of quality. An increase in λ leads to the improvement of robustness, but the system performance quality indicators deteriorate. A decrease in λ, by contrast, improves quality indicators, but degrades the robustness. Thus, λ serves as an efficiency indicator or a measure of quality. This parameter can be used for the procedure of finding a compromise between the quality of control and the robust stability of a closed system.

The main features of controllers of this type for the objects with self-alignment is that they can be adjusted for the quantitative indicators of quality and reliability [12, 13]. Such a possibility remains also for the systems with integral objects. Dependences between a measure of quality and the main indicators of system quality can also be derived unambiguously.

When modeling systems with the H_∞-IMC-controller, we established boundary values for the measure of quality: λ_{min}=0,1τ and λ_{max}=1,20τ. Until the measure of quality is greater than the lower bound λ_{min}, the closed system is stable. An increase in the measure of quality over λ_{max} does not lead in most cases to the improvement of a quality indicator. In addition, for the objects of first order, in this case, it is possible to obtain negative setting parameters for the given PID-controller.

As a result of the conducted modeling of the system with objects without self-alignment of first and second order and the H_∞-IMC-controller, it was found that specific values of quality indicators, that is, reduced to the parameters of an object, depend on the measure of quality of the controller (parameter λ/τ). We investigated frequency indicators (modulus reserve, phase reserve, maximum of a sensitivity function), direct indicators (dynamic error, attenuation degree, re-regulation, increasing time, regulation time) and integral indicators (integral quadratic criterion, integral time quadratic criterion, integral time absolute criterion).

In particular, Fig. 3–5 show dependences of certain quality indicators on parameter λ, which provides an assessment of quality. It is possible to see that the stability reserve by modulus *m* (Fig. 3), attenuation degree ψ (Fig. 4), and regulation time t_{reg} (Fig. 5) unambiguously depend on λ/τ. Other quality indicators are also unambiguously related to λ/τ.

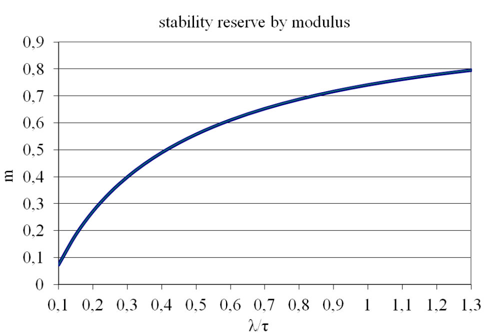

Fig. 3. Impact of the measure of quality on the stability reserve by modulus

By employing these dependences, it is possible to design the H_∞-IMC-controller for the quantitative nominal quality. For example, if a permissible attenuation degree should be 90 %, then, according to Fig. 4, it is necessary to take λ=0.41τ.

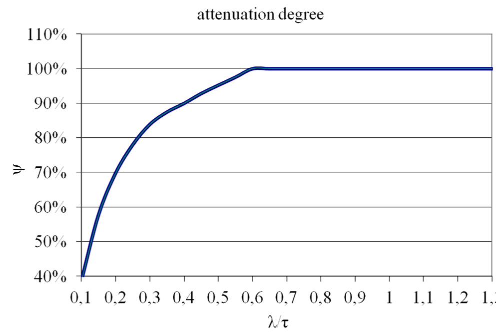

Fig. 4. Impact of the measure of quality on attenuation degree ψ

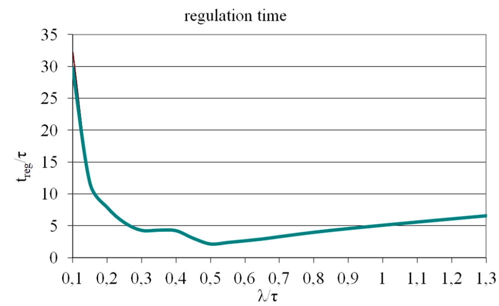

Fig. 5. Impact of the measure of quality on regulation time t_{reg}

Dependences of the main quality indicators can be represented in graphical or analytical form. However, for practical implementation, it is more convenient to use tabular data with a certain programmable control, which facilitates the search for the required results in a data array.

Based on the dependences derived, we created a program that makes it possible to choose such setting parameters of the controller that meet the assigned parameters of the object and the introduced indicators of operation quality (Fig. 6).

Such controller is robust and guarantees attaining the assigned quality indicators.

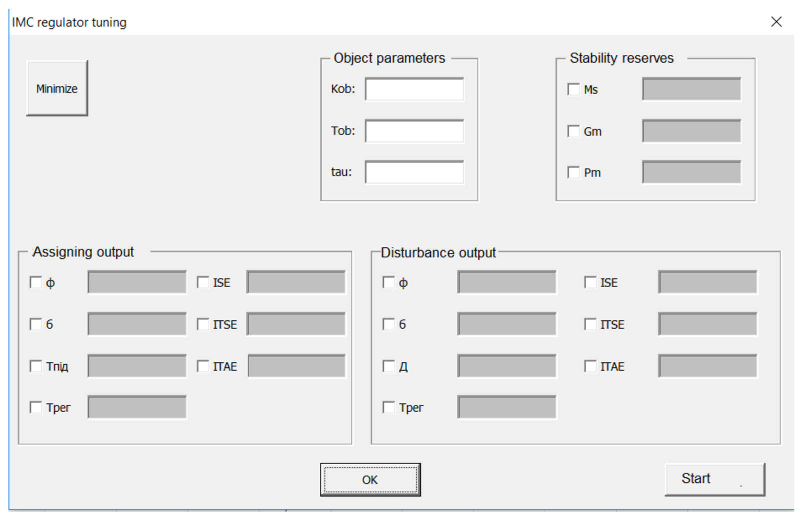

Fig. 6. Interface of the program that selects parameters of the controller

Moreover, it is possible to set more than one initial quality indicator, several at a time. After introducing parameters of the object and assigning required indicators of the system operation quality, the program produces controller's settings that meet the specified requirements. Thus, if one knows a model of the control object with the boundaries of changes in the parameters, it is possible to set the value of the desired indicator or a set of indicators for the system operation quality and obtain the settings of the controller.

6. Discussion of results of the study into an impact of the controller's parameter on the robust system quality

In contrast to the fact that there were developed many methods for the synthesis of controllers, a region of effective work of each method is too limited and requires meeting conditions and constraints, which often do not match real situations. Practical requirements to the operation of control system are typically defined in terms of temporal region or in the frequency domain. Using the targeted setting of the proposed controller, it is possible to ensure the quantitative quality indicators in a closed system.

Based on results of the research conducted, we propose the following procedure for setting a robust controller for the system to demonstrate a value of the selected quality indicator not worse than the assigned one given all the uncertainties of the object:

1) development of a controller for a nominal object with the assigned quality indicator;

2) replacement of the nominal object with the object with the worst combination of parameters (that is, coefficient of object transition and delay time is assigned maximal value);

3) establishing such a measure of quality at which the system operation quality indicator acquires maximally permissible value.

Thus, when the control object model is known, as well as the boundaries of changes in its parameters, it is possible to design a robust controller (17) or (24). Next, by employing a procedure for selecting λ, it is possible to achieve the desired quality by direct quality indicators of functioning for the object in its "worst" state. In addition, a combination of these indicators is very important and meaningful to practicing engineers. This controller will provide robustness of the system with quality indicators not inferior to those assigned.

The study completed is continuation of the work on the synthesis of robust controllers for objects with self-alignment. They can also be adjusted for the quantitative quality and robustness. It is obvious that formulae for controllers in the systems with objects without self-alignment are more complex than those used for stable objects. This is linked to the fact that the integral objects are harder to control.

Obtained controllers could be used in the systems with unstable objects, caused by the presence in their composition of the integral links of first and second order. In further research, it is possible to expand the scope of application for unstable objects having poles in the right part of the complex plane.

7. Conclusions

1. We developed a structure of the controller using an internal model based on the H_∞-norm of a closed system for control object without self-alignment. Such controller is guaranteed to obtain a robust system by the assigned quality indicator.

2. The unambiguous dependences are derived of key quality indicators of the system operation on the parameter of setting a controller for objects without self-alignment of first and second order. Using the received dependences, it is possible to adjust the H_∞-IMC-controller on the preassigned requirements for the transition process and stability reserves. Settings of the controller are directly related to practical requirements for control systems.

3. Based on the dependences derived, we created a program that makes it possible to select the setting parameters of the controller. The resulting robust controller is guaranteed to achieve quality indicators not inferior to those assigned.

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MODELING OF DAILY TEMPERATURE MODE IN PREMISES USING A PREDICTIVE CONTROLLER

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Розглянуті проблеми енергозбереження теплових ресурсів при теплопостачанні офісних будівель і приміщень. У середовищі ANSYS Fluent побудована теплова модель приміщення для перевірки алгоритмів управління температурним полем. Показано, що для забезпечення заданих комфортних умов у приміщенні необхідно використовувати регулятор з передбаченням, який враховує температуру зовнішнього повітря, вентиляцію та систему опалення

Ключові слова: моделювання теплового поля, регулятор с передбаченням, широтно-імпульсна модуляція (ШІМ), ШІМ-регулювання, теплопостачання офісних будівель

Рассмотрены проблемы энергосбережения тепловых ресурсов при теплоснабжении офисных зданий и помещений. В среде ANSYS Fluent построена тепловая модель помещения для проверки алгоритмов управления температурным полем. Показано, что для обеспечения заданных комфортных условий в помещении необходимо использовать регулятор с предсказанием, учитывающий температуру наружного воздуха, вентиляцию и систему отопления

Ключевые слова: моделирование теплового поля, регулятор с предсказанием, широтно-импульсная модуляция (ШИМ), ШИМ-регулирование, теплоснабжение офисного здания

1. Introduction

One of the main sources of power consumption worldwide is the use of power in both residential and commercial premises. Data show that nearly 40 % of total power consumption in the USA [1], and 40 % in the EU, account for the operation of residential and commercial buildings [2]. More than 66 % of current electricity consumption is utilized in residential, administrative and office buildings [3].

Depletion of natural power resources and increasing costs of their extraction and processing make most countries worldwide search for technologies, aimed at enhancing efficiency of using power, rather than on an increase in its production volume.

In the countries of the European Union, approaches to reduction of power consumption and heat savings have been developed for 25 years. Over the past 15 years, demand for heat power decreased due to adoption of national laws, rules and administrative provisions that have been developed by the public authorities [2].

The project "Power strategy of Ukraine for the period to 2035" argues about a low level of power efficiency and predominance of power-consuming industries in its structure [4].

Until recently, the state and the society of Ukraine continued to operate by inertia of stereotypes about the existence of surplus of power resources. The state economic policy did not stimulate their effective use.