# Modeling and Robust Optimization of the Technological Mode of Electrotechnological Complexes with the Renewable Energy Systems of Heat

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**Abstract.** The article works out the structure of the relationship between the managerial lev els of the food enterprise, which is developed taking into account the use of robust control systems in the abnormal mode and systems of repair of heat power. To optimize renewable energy systems to the existing range of technological equipment of the bakery, a cogeneration unit is installed, due to its ability to generate and consume both heat and electricity. Also it is shown that the emergence of an abnormal situation at the electrotechnological complex of food production leads to a significant change in the transfer coefficients of the object over the direct and cross-channel channels, which will lead to loss of stability of the closed control system. Synthesized structure robust control system which has roughness properties and minimal sensitivity to parametric and structural uncertainties facility in case of emergency situations and elected its optimization criterion. The basic properties of the electrotechnological complexes of food industries are analyzed and on the example of the baking furnace the robust control system synthesis and renewable energy systems are shown. A comparison of the characteristics of the control system with local and robust controllers has shown that a robust controller system has better robust properties in case of emergency situations.

## 1 Introduction

Systems of automated control of the food industry electrotechnological objects at the regular mode operate according to the criterion defined by the technological regulations [1], this may be an integral quadratic criterion, minimization of the time of regulation, etc. In this case, the calculation of control device configuration parameters is usually carried out for a linear model with constant coefficients taking into account the stability of the system. At

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the moment of system transition into abnormal mode, the structural and parametric uncertainty of the system significantly increases, and the control system may lose its stability.

In abnormal mode, the technological process operates under conditions of significant uncertainty [2], with only a few of them can be calculated numerically. All uncertainties in the design of the control system can be divided into several types:

- signal uncertainties (external);
- parametric and structural uncertainties of the object model (internal).

When describing the mathematical model of object the uncertainties mast be described by a certain class of uncertainties. Also, when designing the control system of the technological object the uncertainties are arised in the mathematical description of the control criterion that is following from the control purpose (uncertainty of purpose) and the calculation of the control device. In addition, when operating a designed control system, there are additional errors that lead to operational uncertainties, namely: the errors of primary and secondary transducers; errors of the digital converters of the control device, errors of communication lines of the control system. These operational uncertainties are went into the precision class of the respective device, and their total error can be calculated as the sum of dispersion of the respective devices. In order to ensure the stability of the system, it is proposed to use robust control systems in the abnormal mode.

## 2 Problem statement

Robust theory from the outset was created as a theory of designing control systems in the presence of perturbations, about which the developer has virtually no information except the assumption of their limited. Therefore, control algorithms obtained on the basis of this theory are more universal than those obtained without taking into account the presence of perturbations according to different criteria [3, 4].

A characteristic feature of robust systems is that additional information is not used in the process of their operation [5]. This means that the regulator in such system must ensure performance of its work with the given properties throughout the entire work period. For the overall evaluation of the control system, the sensitivity index is also used: the dependence of the control system dynamic properties on any deviations of its parameters and characteristics from the values taken as the initial or calculated.

In robust theory, the mathematical model of the control object is presented as a class of uncertainty [3], for example, widespread models with structural dynamic uncertainty of the electrotechnical complex is

$$\left[I+\Delta(s)W_{\Delta}(s)\right]G_0(s), \quad \left\|\Delta(s)\right\|_{\infty}<1, \tag{1}$$

where $G_0(s)$ – is transfer function of the nominal object, $W_{\Delta}(s)$ –is weight transfer function that determines the scale of uncertainty and the frequency range in which it operates; $\Delta(s)$ – is transfer function of structural uncertainty. In the general case, all transfer functions in (1) are matrix.

Today, the theory of robust optimal control can be divided into the following directions [3-9]: Loop Shaping synthesis, "2-Riccati" approach, μ-Synthesis Approach, LMI, $l_1$-

theory. Another approach that came about ten years ago within the framework of the $H_\infty$-theory is the nonsmooth synthesis method [4, 5]. This method is based on the numerical optimization of non-smooth criteria, in particular the $H_\infty$-norm of a closed system or other system characteristics. In contrast to the above analytical methods, here the structure of the controller is given by the designer, and the parameters are determined by optimization.

Thus, within the framework of a robust theory, in order for the system to have robust properties, the $H_\infty$ criterion is chosen, and the setting of a robust regulator, such as a traditional PI, is calculated using the nonsmooth multy-directional search. The advantages of such systems are unquestionable - the designer of the control system can personally choose any structure of the regulator and the calculated regulator has the properties of robustness, since it is synthesized by the $H_\infty$ criterion.

## 3 Materials and methods

The criterion for functioning of an electrotechnical complex is given by the production level that is the level of management of production operations (MOM / MES), which is formed on the basis of economic criteria and limitations of the level of business planning and logistics (ERP). In fig. 1 shows a simplified scheme of the relationship of managerial levels of the food business, developed on the basis of the factor-target model of the electrotechnological complex (ETC) of food industries [10] and taking into account the use of abnormal modes of robust control systems. The management of production operations is the actions of the 3rd level of the production activity of the enterprise, which coordinate the regime indicators of the technological process, the work of personnel, equipment and the use of materials in production (ISA-95).

Each production operation can be presented as an optimization task, the solution of which are given technological variables, which ensure the optimal functioning of the technological complex. Optimal technological variables, such as temperature, pH, flow, etc. are transmitted to the lower level - automatic control of ETC as the specified values of dynamic optimization of this level. To minimize the effects between the subsystems of the horizontal level of automatic control of the ETC, the use of robust algorithms for the synthesis of the control device is effective. The latter provide coarse control of technological objects in conditions of significant uncertainty, thereby minimizing the influence between subsystems of the electrotechnological complex [11].

To optimize renewable energy systems to the existing range of technological equipment of the bakery, a cogeneration unit is installed, that is caused by the possibility of generation and consumption, both heat and electricity. The task of such equipment is the restoration of heat energy from the flue gas for its transfer to the boiler plant and the generation of economically feasible volumes of electricity for industrial consumers of such energy resources.

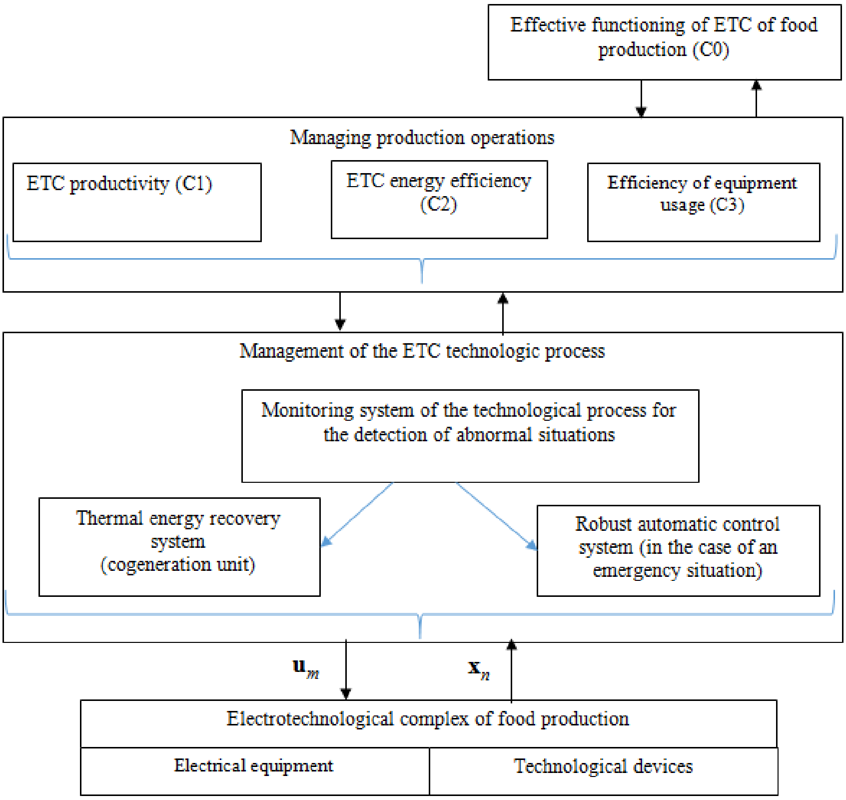

**Fig. 1.** Generalized universal structure of the relationship management levels of the food enterprise.

This approach meets the concept of distributed generation ("Smart Grid" -technology), which allows you to count on the following effects:

1. Increase of consumer reliability;
2. Energy security - by expanding the types of fuel, attracting local energy resources;
3. Optimize load control and backup;
4. Ensuring the function of flexibility of "smart networks" (in terms of generation);
5. Energy efficiency - optimization of load curve, reduction of losses in the process of transmission / distribution of energy, expansion of cogeneration, etc.;
6. Reducing the environmental load (CO2 emissions).

The proposed solution can be attributed to the "Smart Grid" technology with the following innovative properties that meet the new needs of electrical engineering complexes and systems, among which the following can be distinguished:

– An active two-directional scheme of interaction in a real-time information exchange between elements and participants of the network, from power generators to end-use power devices.

– Coverage of the whole technological chain of the electric power system, from energy producers (as central, NPP, CHP, HES, and autonomous - cogeneration plant).

– Support of information exchange in the "Smart Grid" provides for the use of digital communication networks and data interfaces.

In the first stage, for the simulation and optimization of renewable energy systems and the creation of a robust automated control system by an electrotechnological complex, it is necessary to obtain linear mathematical models of thermal processes.

To obtain a mathematical model of the heat exchange part of the boiler house on the basis of thermal and material balances, one can adopt the approach wrote in [12, 13].

After bringing the mathematical model to the standard form, we obtain:

$$\begin{cases} T_1 \dfrac{d\Delta\theta_{11}}{d\tau} + \Delta\theta_{11} = K_{11}\Delta\theta_{10} + K_{12}\Delta G_1 + K_{13}\Delta\theta_{n1} \\ T_2 \dfrac{d\Delta\theta_{21}}{d\tau} + \Delta\theta_{21} = K_{21}\Delta\theta_{20} + K_{22}\Delta G_2 + K_{23}\Delta\theta_{n2} \\ T_3 \dfrac{d\Delta\theta_{n1}}{d\tau} + \Delta\theta_{n1} = K_{31}\Delta G_{n1} + K_{32}\Delta\theta_{10} \\ T_4 \dfrac{d\Delta\theta_{n1}}{d\tau} + \Delta\theta_{n1} = K_{41}\Delta G_{n2} + K_{42}\Delta\theta_{20} \end{cases}$$

where constant time $T_i$ and transfer rates $k_{ij}$ are calculated by the formulas:

$$T_1 = \frac{V_1 \rho C_в}{C_в G_{1_0}}; \qquad K_{11} = \frac{(G_1 C_в - k_1 F_1)}{C_в G_{1_0}};$$

$$K_{12} = \frac{\left(C_в \theta_{10_0} - C_в \theta_{11_0}\right)}{C_в G_{1_0}}; \qquad K_{13} = \frac{k_1 F_1}{C_в G_{1_0}};$$

$$T_2 = \frac{V_2 \rho C_в}{C_в G_{2_0}}; \qquad K_{21} = \frac{(G_2 C_в - k_2 F_2)}{C_в G_{2_0}};$$

$$K_{22} = \frac{\left(C_в \theta_{20_0} - C_в \theta_{21_0}\right)}{C_в G_{2_0}}; \qquad K_{23} = \frac{k_2 F_2}{C_в G_{2_0}};$$

$$T_3 = \frac{V_3 C_n}{k_1 F_1}; \qquad K_{31} = \frac{r_1}{k_1 F_1};$$

$$K_{32}=1; \qquad T_4=\frac{V_4C_n}{k_2F_2};$$

$$K_{41}=\frac{r_2}{k_2F_2}; \qquad K_{42}=1.$$

where $\Delta\theta_{ni}$ is deviation of the temperature of the heating steam in the *i*-th heat exchanger; $\Delta G_1$ is deviation of the flow of water, consuming to production; $\Delta G_2$ is deviation of the flow of water, consuming to the household needs of the enterprise; $\Delta\theta_{10}$ is deviation of water temperature, consuming to production at the entrance to the heater; $\Delta\theta_{11}$ is deviation of water temperature, which goes into production after the heater; $\Delta\theta_{20}$ is deviation of water temperature, consuming to the household needs of the entrance to the heater; $\Delta\theta_{21}$ is deviation of water temperature, consuming to the household needs of the company at the outlet of the heater.

The values of the transfer coefficients of the mathematical model of the heat exchanger part of the boiler house were calculated for typical operating modes taking into account the design features of heat exchangers installed in the boiler-house of the bakery (Fig. 2, 3).

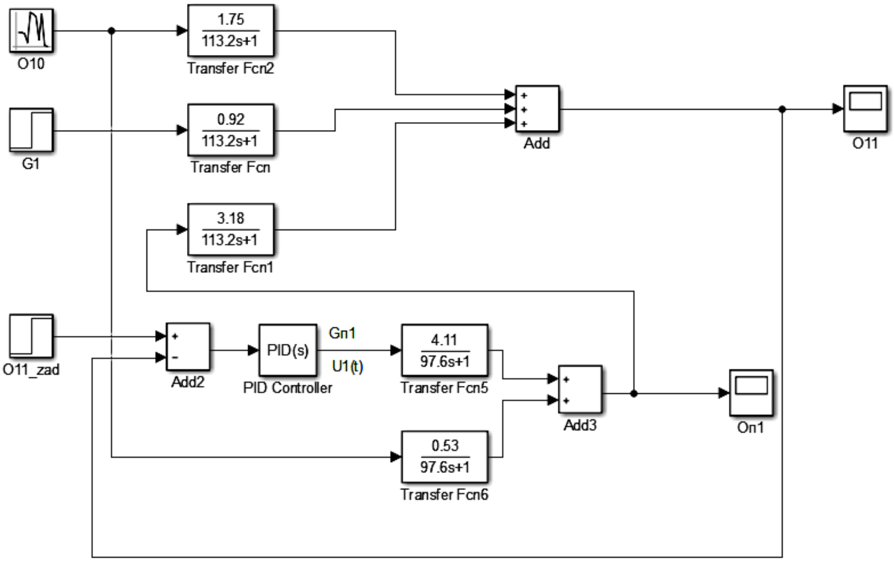

**Fig. 2.** The block diagram of the system of automated control of the water temperature, consuming to production.

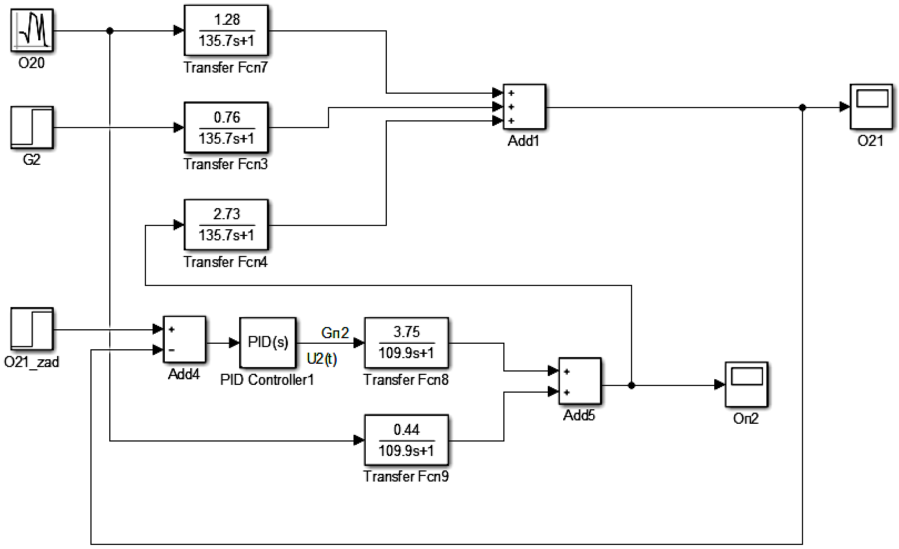

**Fig. 3.** The block diagram of the system of automated control of the water temperature, consuming to household needs.

The values of the coefficients of heat transfer for the 1st and 2nd heat exchangers were determined depending on the material from which the heat exchangers were made: austenitic steel with high corrosion resistance.

The heat transfer coefficient of austenitic steel for a single-layer flat wall is determined by the formula:

$$k = \frac{1}{R_{\alpha г} + R_{cm} + R_{\alpha x}} = \frac{1}{1/\alpha_г + \left(\delta/\lambda\right)_{cm} + 1/\alpha_x},$$

where $\alpha_г$ and $\alpha_x$ is the coefficient of heat transfer from the hot coolant to the wall and from the wall to the cold coolant, respectively; $\delta$ and $\lambda$ is thickness and coefficient of thermal conductivity of the wall; $R_{\alpha г}$ is thermal resistance of heat transfer from the side of the hot coolant; $R_{cm}$ is thermal resistance of the thermal conductivity (walls); $R_{\alpha x}$ is thermal resistance of heat transfer from the cold coolant.

To maintain the required temperature regime of the boiler house we use PI regulators, the equations of which have the form:

$$U_1(t) = k_{1P}\Delta\theta_{11} + k_{1I}\int_0^t \Delta\theta_{11} dt,$$

$$U_2(t) = k_{2P}\Delta\theta_{21} + k_{2I}\int_0^t \Delta\theta_{21} dt\,.$$

The optimal settings of the regulators were determined by the method of non-vanishing oscillations: $K_{reg} = 0.45 \cdot K_{kr}$, $T_i = T_{kr}/1.2$, where $K_{kr}, T_{kr}$ is the critical values of the transmission coefficient and the period of fluctuations in the system. Below are transient processes for controlling the water temperature at the outlet from the heat exchanger when the task and perturbation are changed (Fig. 4 - 7).

As a result of the simulation, a system of automatic temperature control in the boiler house has been obtained, which allows one to determine: whether the amount of renewable thermal energy produced by the cogeneration plant is sufficient for the normal operation of the boiler room.

Based on the previous results, a robust control system and advanced dynamic mathematical models are used to evaluate the temperature operating conditions of the baking oven and the boiler house.

The construction of an effective control system is preceded by the construction of an adequate mathematical model of the object. The advantage of robust systems is the use of a simple, in particular, linear mathematical model of an object, whereas non-stationary, nonlinear, and other factors, which lead to a rejection of the functioning of the system from the nominal state, are taken into account in the description of various types of uncertainties.

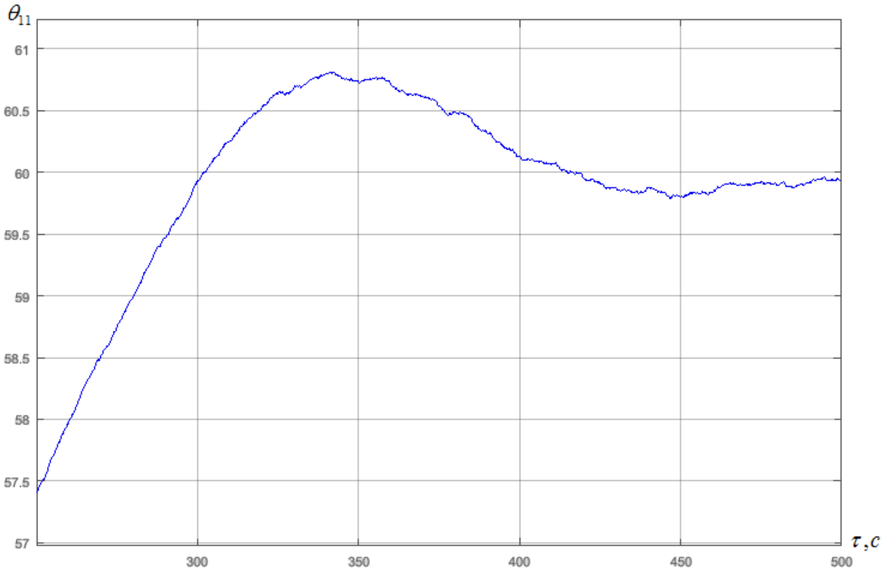

**Fig.4.** Transitional process of water temperature regulation, which goes into production when the task is changed ( $\theta_{11\_pred} = 60^0 C$ ).

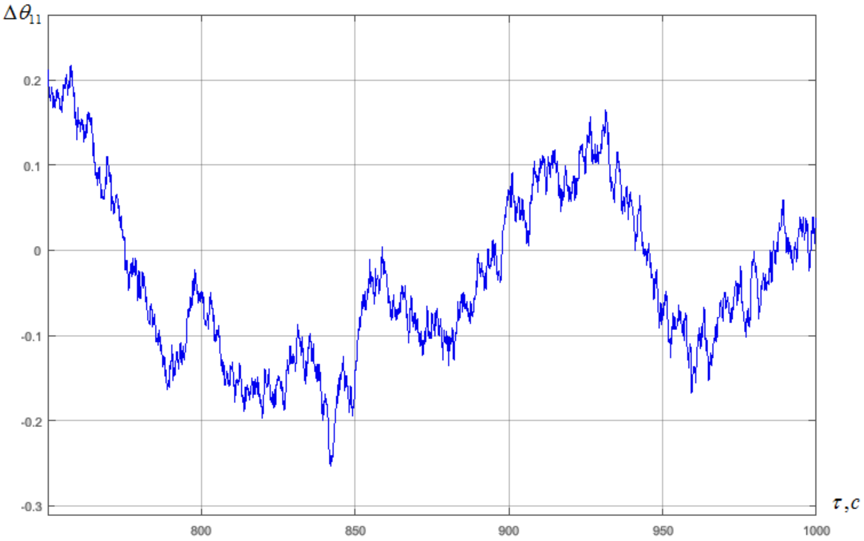

**Fig.5.** Transitional process of regulating the temperature of water entering the production relative to the action of perturbation (changes in the deviation of water temperature at the entrance to the heater).

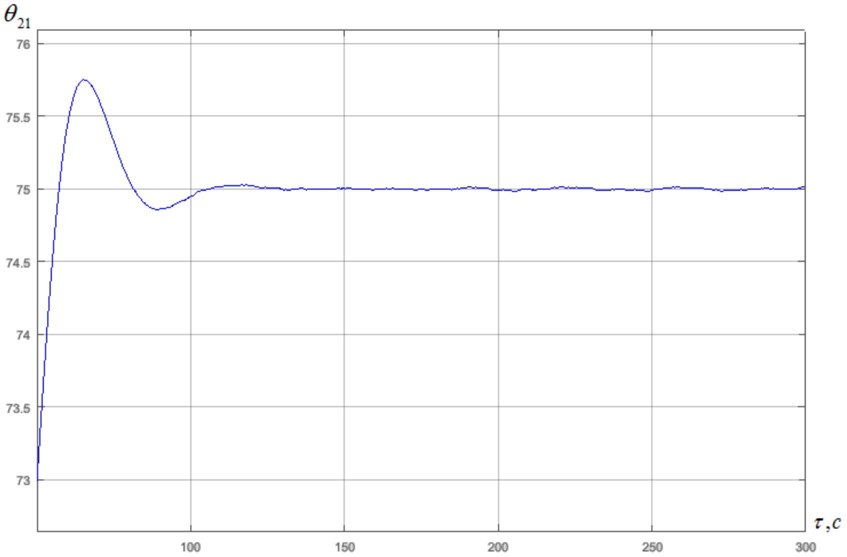

**Fig.6.** Transitional process of regulating the temperature of water, consuming to the household needs of the enterprise when changing the task ( $\theta_{21\_pred} = 75^0 C$ ).

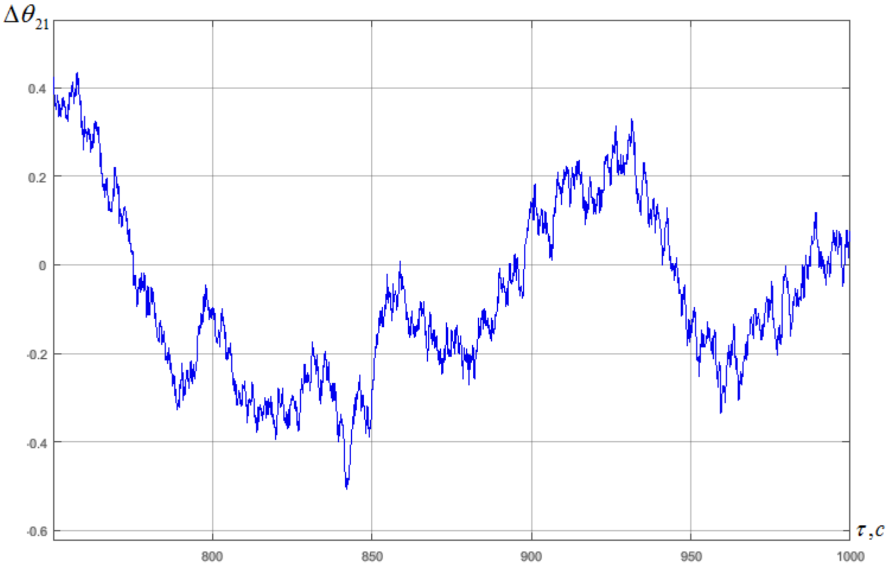

**Fig. 7.** Transitional process of temperature control of water, consuming to the household needs of the enterprise relative to the effect of perturbation (changes in the deviation of water temperature at the entrance to the heater).

In general, the mathematical model of the control object can be written as

$$\mathbf{x} = F(\mathbf{u}, \mathbf{z}), \tag{2}$$

where *x* is the coordinate vector of the state of the system, dimension *n*; u is the vector of controls, dimension *m*; *z* is the vector of perturbations, dimension *l*; *F* is the operator or function (vector-function) of the object mathematical model. The operator F can be given in different ways: using formulas, tables, graphs.

In practice, when we are designing a control system for technological processes of food businesses, we do not use nonlinear models, and by linearization we move to a linear model of an object in the form of transfer functions:

$$\mathbf{x} = \mathbf{G}(s)\mathbf{u}, \tag{3}$$

and, as a rule, in a scalar form. Transfer function of the control object is obtained by to conducting an active experiment when feeding to the control input of the periodic (step, pulse) or periodic signals (sinusoidal, pseudobinarny etc.). In this case, the structure of the transfer function of the object is chosen according to a priori information. If information about the structure (3) we do not have, then, as a rule, we take an aperiodic link with a delay for an object with self-alignment, or an integral link with a delay for an object without self-alignment. Note that without identifying an object's mathematical model, the regulator may not be able to adjust, or it will take a long time.

Next, the linear structure regulator is constructed according to one of the engineering criteria of the quality of the transients, after which the stability reserve of the control system is adjusted. At the last stage, the designer "desensitizes" the control system, usually by reducing the transmission coefficient of the proportional component PI or other controller. In summary, the design of the control system is far from the optimal mode of operation.

One of the effective ways to ensure the robust properties of the system with one input - one output is the use of the theory of sensitivity, as well as the loop shaping approach based on this theory. This is a generalized classical method that uses the logarithmic amplitude-frequency characteristics of the open system (Bode diagram).

Within the framework of this approach [3] we consider a system described by three transfer functions:

$$\mathbf{e}=\mathbf{S}(s)\mathbf{r},\ \mathbf{u}=\mathbf{R}(s)\mathbf{r},\ \mathbf{y}=\mathbf{T}(s)\mathbf{r}, \tag{4}$$

where **S**(s) is the transfer function of the sensitivity of the system, **T**(s) is a function of additional sensitivity and additional transfer functions **L**(s) and **R**(s), which are determined by the formulas:

$$\mathbf{L}(s)=\mathbf{G}(s)\mathbf{K}(s),\ \mathbf{S}(s)=[\mathbf{I}+\mathbf{L}(s)]^{-1},\ \mathbf{R}(s)=\mathbf{K}(s)[\mathbf{I}+\mathbf{L}(s)]^{-1},$$

$$\mathbf{T}(s)=\mathbf{L}(s)[\mathbf{I}+\mathbf{L}(s)]^{-1}. \tag{5}$$

The indicated three transfer functions (4), (5) determine the quality and robustness of the multidimensional system. In particular, the function **S**(s) describes the change of the closed system to small parametric or structural deviations of the object. In addition, this same function determines the qualitative measure of tracking the signal of the task **r**(t), which depends both on the signal **r**(t) and on the measurement of the tracking error **e**(t). For example, if a sinusoidal signal with amplitude ≤1 arrives at the input of a task, and it is necessary to obtain e (t) with amplitude ≤ε, then the tracking quality can be expressed as:

$$\|\mathbf{S}(s)\|_\infty < \varepsilon \quad \text{або} \quad \|\mathbf{W}_{s1}(s)\mathbf{S}(s)\|_\infty < 1, \tag{6}$$

where $W_1(s) = 1/\varepsilon$ is the weight function, which in the general case may depend on the frequency.

In accordance with this theory, the size of the largest destabilizing additive and multiplicative uncertainty can also be calculated numerically:

$$\begin{aligned} \bar{\sigma}(\mathbf{\Delta}_A(j\omega)) &= \frac{1}{\bar{\sigma}(\mathbf{R}(j\omega))}, \\ \bar{\sigma}(\mathbf{\Delta}_M(j\omega)) &= \frac{1}{\bar{\sigma}(\mathbf{T}(j\omega))}. \end{aligned} \tag{7}$$

where $\bar{\sigma}(\ )$ is the largest singular value of the corresponding transfer matrix. Similarly, for $\mathbf{S}(s)$ we determine the weight functions for the matrices $\mathbf{R}(s)$ and $\mathbf{T}(s)$.

In non-standard mode, the technological process is subject to destabilizing internal influences, which appear in the mathematical model of the object as parametric and multiplicative uncertainties. Thus, by the criterion of optimization you can choose the expression:

$$\left\| \begin{matrix} \mathbf{W}_1(s)\mathbf{S}(s) \\ \mathbf{W}_2(s)\mathbf{T}(s) \end{matrix} \right\|_\infty \to \min_{\mathbf{K}(\boldsymbol{\theta},s)}, \tag{8}$$

where $\mathrm{K}(\Theta, s)$ is the transfer function of the regulator with the parameter vector $\boldsymbol{\theta}$. The structure of the regulator $\mathrm{K}(\Theta, s)$ can be selected independently based on a priori data on the operation of the technological object and the simplicity of implementation. Note that criterion (8) is a kind of so-called "weighted mixed sensitivity" tasks whose solution is reduced to a "2-Rikkat" -flow without specifying the structure of the regulator. However, in this paper, we propose to solve the optimization problem (8) by the method of non-smooth synthesis, thereby fixing the structure $\mathrm{K}(\Theta, s)$.

Thus, we will formulate the main stages of constructing a robust controller:

- construction of mathematical model of technological process;
- determination of management criterion and weight functions;
- experimental modeling of the control system;
- implementation of the received regulator on a technical basis.

After analyzing the peculiarities of the technological processes of food production, we can conclude that the food enterprises are complex electrotechnical complexes that have the following main features as objects of management:

- the components of the electrotechnological systems of food production have the same structure of the electrical equipment and energy supply systems of the enterprise, and differ only in technological equipment;
- the structure of food production is hierarchical (products of one production process are the raw material for other production processes).
- high dimension of data, high degree of uncertainty of work and concealment of quality indices of raw materials and semi-finished products.
- multipurpose object behavior, when the priority of the objectives of each subsystem depends on the overall situation on the control object.

A typical representative of the ETC of food production is the bakery, so let's give an example of the development of a robust control system in the case of a non-emergency situation for a bakery oven.

The baking oven can be represented as a multi-parameter monoelement object, which is characterized by a number of technological and thermal engineering variables. The baking oven is being divided into separate, characteristic structural features, sections, each of which is considered as a linear one-dimensional object with lumped parameters and its input and output actions.

The mathematical model of a baking oven in the space of state variables has the form:

$$\frac{d\mathbf{x}(t)}{dt} = \mathbf{A}\mathbf{x}(t) + \mathbf{B}_1\mathbf{z}(t) + \mathbf{B}_2\mathbf{u}(t), \qquad \mathbf{y}(t) = \mathbf{C}\mathbf{x}(t); \tag{9}$$

where

$$\mathbf{x}(t) = \begin{bmatrix} \Delta\theta_{fg}(t) \\ \Delta\theta_c(t) \\ \Delta W(t) \end{bmatrix}; \quad \mathbf{u}(t) = \begin{bmatrix} \Delta G_f \\ \Delta G_n \end{bmatrix}; \quad \mathbf{z}(t) = \begin{bmatrix} \Delta G_{rec} \\ \Delta\theta_{rec} \\ \Delta G_x \\ \Delta P_n \end{bmatrix}; \quad \mathbf{y}(t) = \begin{bmatrix} \Delta\theta_c(t) \\ \Delta W(t) \end{bmatrix}. \tag{10}$$

Notation: $\Delta G_f$ is fuel consumption, supplied to the furnace, kg / h; $G_{rec}$ is consumption of recirculation gases entering the furnace, m$^3$; $\theta_{rec}$ is temperature of recirculation gases, $^0$C; $\theta_{fg}$ is temperature of flue gases, $^0$C; $G_x$ is steam consumption for humidification, kg / h; $G_n$ is power of the oven, kg / h; $P_n$ is partial vapor pressure in the chamber baking kPa; $\theta_c$ is temperature in the baking chamber, $^0$C; $W$ is humidity in the baking chamber, %.

The coefficients of the mathematical model for the real object (11) are calculated according to the static parameters of the process, which depend on the structural features of the apparatus and the heat capacity of the substances and walls, which, in assumptions, were accepted as lumped and constant:

$$\mathbf{A} = \begin{bmatrix} -0.84 & 0 & 0 \\ 0.22 & -0.50 & -0.10 \\ 0 & -0.03 & -0.23 \end{bmatrix}, \tag{11}$$

$$\mathbf{B}_1 = \begin{bmatrix} -0.07 & 0.55 & 0 & 0 \\ 0 & 0 & -0.10 & 0 \\ 0 & 0 & 0 & 0.002 \end{bmatrix}, \ \mathbf{B}_2 = \begin{bmatrix} 3.80 & 0 \\ 0 & 0 \\ 0 & 1.04 \end{bmatrix},$$

$$\mathbf{C} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

We note that a mathematical model for the synthesis of a robust regulator can also be obtained by an experimental connection by the aperiodic or periodic input actions for each channel. In this case, the mathematical model is obtained in the form of elementary transfer functions, such as an aperiodic or integral link of the first order with a delay, an aperiodic or integral link of the second order, etc. Regardless of how the mathematical model of an object is obtained, it can easily be transformed into a space of state variables, and then we synthesize a robust controller. Because the processes have large time constants, the control device, synthesized by continuous synthesis algorithms, will make a minor mistake in the system. On the other hand, as it is known, the discrete mode of operation of the control device makes a delay in the control system, but the robust system properties take into account the inaccuracies of the object model.

Consider changing the behavior of the object in non-regular mode. In fig. 8 shows changes in the transient response when introducing parametric and multiplicative uncertainties in an object. As we see, transmission coefficients for direct channels vary about 2 times, and for cross-links vary and more. Such an increase in transmission coefficients will result in loss of stability of the closed system.

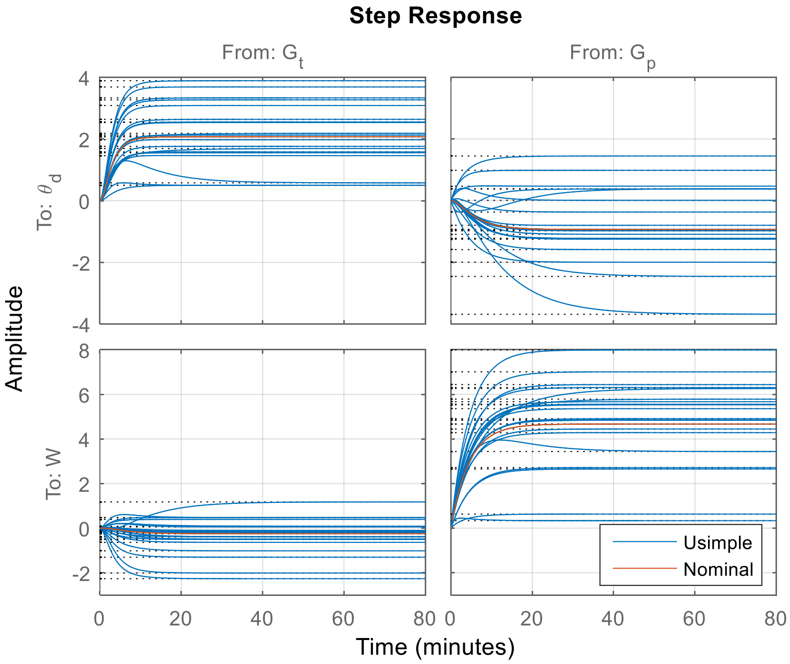

**Fig. 8.** Curves series of the object's transient response for control channels.

We synthesize management system that consists of two PI regulators and works in normal mode. As the control criterion we will select the maximum perturbation filtration with a $45^0$-degree stability reserve. In fig. 9 shows transient processes in a closed system when the task and perturbation are changed (red line is a nominal object; the blue line is an object with random uncertainty). As you can see, when introducing uncertainties into the object control system has poor qualitative characteristics.

In accordance with the above method, the robust parameters of the PID regulators and the static compensator according to criterion (8) were synthesized. The structural scheme of the received control system is shown in Fig. 10. For comparison parameters PID controller of two systems are shown in Table 1.

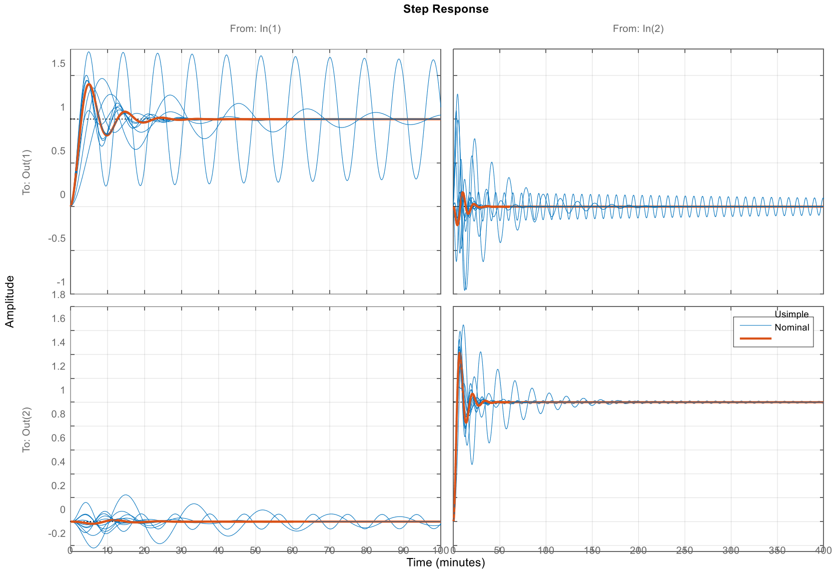

**Fig. 9.** Curves series of transient processes in the local system relative to the change of task at random values of uncertainty.

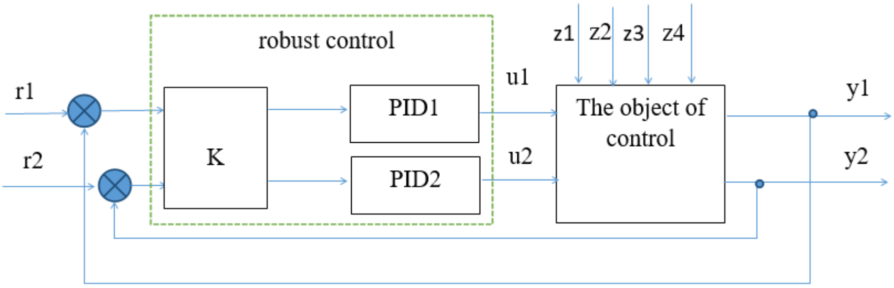

**Fig. 10.** Structural scheme of the robust control system.

**Table 1.** Parameters of controllers synthesized according to different criteria.

| System | Parameters of controllers<br>$\mathrm{Kp} + \mathrm{Ki}\frac{1}{s} + Kd\frac{s}{Tf \cdot s + 1}$ |
|---|---|
| 1 ( local ) | PID1: Kp = 0.46, Ki = 0.57, Kd = 0.09, Tf = 0<br>PID2: Kp = 0.03, Ki = 0.21, Kd = 0.001, Tf = 0 |
| 2 ( robust ) | PID1: Kp = 0.50, Ki = 0.50, Kd = 0.06, Tf = 1<br>PID2: Kp = 0.5, Ki = 0.3, Kd =0.05, Tf = 1<br>K: [ 1 -0.2179 -0.2179 1 ] |

In fig. 11 shows transient processes in a robust control system relative to the change of task.

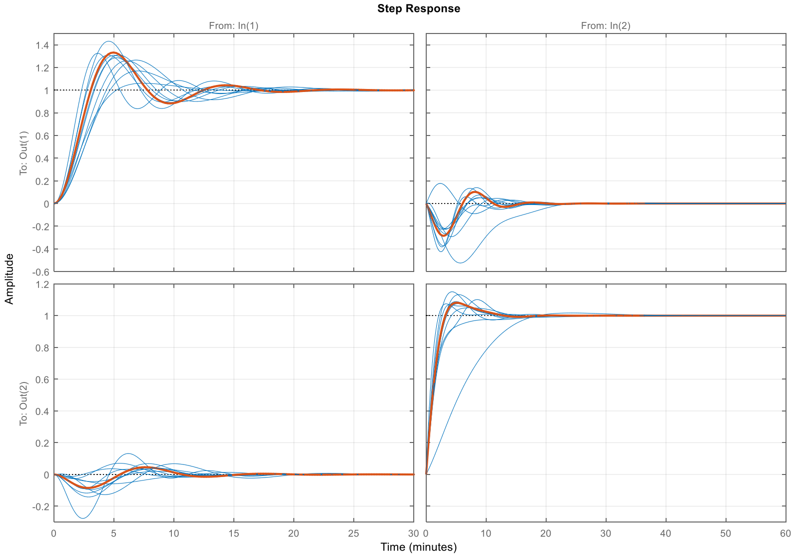

**Fig. 11.** Transition processes in the robust system relative to the change of task at random values of uncertainty.

**Table 2.** Comparative characteristics of systems with different controllers.

| controller | $\|T(s)\|_\infty$ | $\|S(s)\|_\infty$ | $\|R(s)\|_\infty$ |
|---|---|---|---|
| Local system | 1.99 | 2.26 | 2.14 |
| Robust system | 1.75 | 2.00 | 1.80 |

Analyzing table 2 it can be concluded that the robust controller system has better robust properties, namely: the region of parametric and structural uncertainty in which the system remains broadly stabilized by 11%, 14% and 18%, respectively.

From the analysis of the control signals in the systems with regard to the change in the task at nominal values of uncertainty (Fig. 12), the integral quadratic characteristics of each signal are determined: the resource of control on the first channel in the robust system increased by 17%, but by the second channel, respectively, decreased twice (52%). The total integral quadratic indicator of control signals in the robust system has increased from 33.02 units of control measurement$^2$ to 36.76 units of control measurement$^2$.

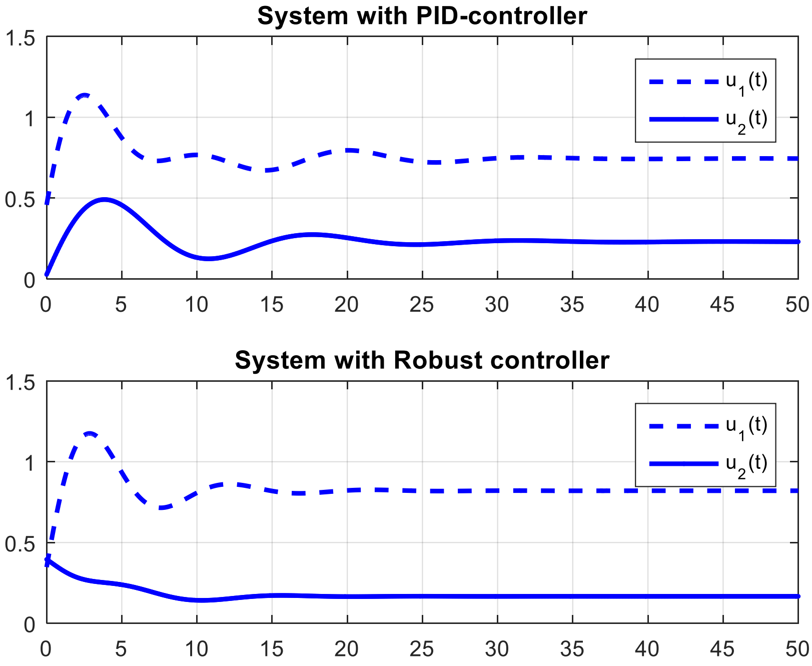

**Fig. 12.** Control signals in nominal systems.

## 4 Conclusions

In order to simplify the implementation of robust control systems by the electrotechnological complex of food production in a non-regular mode, a generalized universal structure of the interconnection of managerial levels of the food enterprise with the consideration of renewable energy systems has been developed.

A simulation of the system of automatic temperature control in the boiler house was carried out to assess the boiler operation mode taking into account the amount of renewable thermal energy produced by the cogeneration unit. The optimization criterion is chosen and the structure of the robust control system is synthesized in the case of an unusual situation that has the properties of rudeness and minimal sensitivity to parametric and structural uncertainties of the object. The simulation was carried out on an example of a baking oven, and the optimal parameters of a robust control system were obtained. Comparison of the characteristics of the control system with local and robust controllers showed that the robust controller system has better robust properties, namely the parametric and structural uncertainty area in which the system remains broadly stabilized by 11%, 14% and 18%, respectively.

The improvement of this system is the development of a coordinating system control for robust subsystems of the electrotechnological complex.

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