Побудована система автоматичного керування з нечітким адаптуючим пристроєм параметрів налаштування ПІ-регулятора в умовах нестаціонарності параметрів моделі об'єкта керування. Виконано математичне моделювання спроектованої системи, проведене дослідження для різних станів об'єкта. Застосування нечіткого адаптуючого пристрою дозволяє забезпечити високу якість функціонування системи при необхідному запасі стійкості в умовах параметричної нестаціонарності досліджуваного об'єкта

Ключові слова: нечітка логіка, нестаціонарність, адаптивна система, запас стійкості, система керування, робастність

Построена система автоматического управления с нечетким адаптирующим устройством параметров настройки ПИ-регулятора в условиях нестационарности параметров модели объекта управления. Выполнено математическое моделирование спроектированной системы, проведено исследование для различных состояний объекта. Применение нечеткого адаптирующего устройства позволяет обеспечить высокое качество функционирования системы при необходимом запасе устойчивости в условиях параметрической нестационарности исследуемого объекта

Ключевые слова: нечеткая логика, нестационарность, адаптивная система, запас устойчивости, система управления, робастность

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DEVELOPMENT OF ADAPTIVE FUZZY-LOGIC DEVICE FOR CONTROL UNDER CONDITIONS OF PARAMETRIC NON-STATIONARITY

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1. Introduction

The task of control over complex technological objects is often accompanied by difficulties whose existence significantly compromises the quality of control systems when applying classic methods of control. One of such negative factors is the variable dynamics of behavior of control object.

The existence of such factors is inherent to many objects in power generation industry. For example, such facilities as wind turbines, solar panels and other alternative and renewable power sources have a major problem in the form of instability of power generation. This is predetermined by seasonal and day cycles, climatic conditions, varying ambient temperature, abnormal weather phenomena, etc.

It is clear that construction of generating facilities with a significant power reserve somewhat solves the problem, but the high cost and a low capacity factor make such a solution economically impractical. Along with this, increasingly important task is the integration of facilities of renewable energy into the overall energy system, which puts forward new requirements to the stability of generation and requires new technical solutions.

Parametrical non-stationarity is quite common for the facilities of traditional energy sector, which employ combustion of different types of organic fuel. However, in many cases, it becomes almost impossible to determine the limits of such non-stationarity for equipment under operation. It is caused, first, by the limits in carrying out experimental research involving the use of such equipment. Second, there is the incompleteness of mathematical description, which is caused by linearization and approximation of characteristics of its elements. At the same time, enabling a stable operation mode, and preferably an optimal regime in terms of energy efficiency, remains one of the greatest challenges. All these factors contribute to significant differences between results of modeling the behavior of synthesized automatic regulation systems (ARS) and actual experimental data, obtained during the start-adjustment process.

An additional factor that causes non-stationarity is the physical wear of technological equipment. Moreover, it is characteristic of both traditional and renewable energy sources.

The described impact of factors, which lead to parametric non-stationarity, makes it relevant to apply the more modern and complex control algorithms. They should provide for small deviations of quality control parameters under conditions of change in the input magnitudes (object parameters) even over a rather wide range. A controller whose design is based on fuzzy logic is considered to be a solution to this problem. In contrast to classic PI-controller, a fuzzy controller, given the correct construct of rule

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base, is capable of operating with an object more efficiently under conditions of parametric non-stationarity. A rule base of the fuzzy controller is built based on the previous experience of control over a target object. This makes it possible to take into consideration all peculiarities of a control object (considering parametric non-stationarity) in the process of control influence generation. This ensures the advantage of fuzzy controller in comparison to the classic PI-regulator.

2. Literature review and problem statement

The most common technique to control technological parameters in industry is the PID law of control. In automatic control systems of technological processes (TP ACS), the PID law is used for about 95 % of various control circuits in the world [1]. Its wide applicability is mostly explained by simplicity of the structure (three setting parameters) and by better understanding by an engineer of the functioning of each component as compared to more complex and modern control methods [2].

Such a wide use led to continuous research aimed at the development of methods for design and calculation of setting parameters for PID- controllers. The number of techniques increased tenfold: from about two hundred in the late twentieth century to 1,731 (563 for PI, and 1,168 for PID algorithms) in 2010 [1]. However, despite such a number of techniques, the task of control over certain thermal power facilities is not completely resolved. For simple cases when requirements to ACS operation quality are not strict, the model is adequate, the situation with disturbances is clear, and thus there are no problems when setting the system. Such operation conditions compose 20–25 % of control systems in industry. At the same time, according to various estimates, 50–55 % of control systems demonstrate their best results at manual control, which is why they either partially operate under automatic mode or do not use it at all (25–30 %) [3]. Specifically, such a situation is observed in controlling the inertial circuits of boiler assemblies at thermal electric power stations (TES). It should be noted that the PID control law is recommended for facilities of low orders [1] whereas TES boiler assemblies of medium and high capacity are the multi-capacious non-linear objects. Second, an important factor for the non-stationary nature of TES boiler assemblies is a change in the technological operation mode. As the main task of control system is functioning over a sufficiently wide range of changes in objects' parameters, input disturbances and loads, the use of the D-component is impractical due to the worsening of robustness of the system in general. The same control system must enable the proper start of an object setting it to a standard operation mode, as well as its operation over a period of maximum load. Each of these operation periods can be characterized by a wide range of parametric non-stationarity of the object's model. Attempts at resolving these problems have changed the vector of research towards adaptive systems and robust control.

A general theory of adaptive control over systems with uncertain parameters and external disturbance without regard to a specific object was developed in [4]. Uncertainty of many parameters of objects during operation requires the application of specialized methods and control systems that have the task to compensate for the lack of information about an object. General classification of the methods to control objects with a large variation in parameters or with unknown characteristics of disturbance was reported in paper [5].

Some interesting solutions have been proposed recently for designing robust systems based on conventional and visual frequency characteristics, as well as based on the internal model control (IMC).

A method of dynamic correction, considered in paper [6], implies the offset of amplitude-phase characteristic of the system. An increase in stability factor and the generation of the required control influence is achieved by using a 2-channel structure. In this case, the main channel is responsible for rapid performance and is based on the PI-law, while the correction channel compensates for an excess signal of the control influence at the final section of transition process, providing for ACS stability. A given controller in fact has no active adaptation at a change in the parameters of an object, but it ensures high quality indicators of system's operation. Such a class of controllers can be attributed to the equivalent-adaptive controllers with variable structure.

Another technique is based on the use of a controller with an internal model. The main advantage is that the stability of the closed system is achieved through choosing a stable IMC controller. The task of synthesis is reduced to the calculation of a single parameter, which is termed a quality measure, and is in fact a parameter of the high frequency filter. Using numerical modeling, it is possible to obtain unambiguous dependences between a quality measure and basic quality indicators of system's operation [2].

The past two decades have witnessed extensive research into the application of fuzzy logic to the tasks on control over technological processes. Fuzzy control, or control based on the theory of fuzzy sets, is employed when there is no sufficient knowledge about a control object (CO), but there is the practice of controlling it. That is, a given control is appropriate in nonlinear or complex systems, identification of which is too labor-consuming, as well as in cases when, by the preset conditions of the task, it is necessary to use expert knowledge [7]. There is typically a shortage of information about a technological process, and a lack of reliable mathematical models that describe it, in order to apply the latest sophisticated control methods [8]. This explains the fact that certain complex processes are effectively controlled manually by experienced operators.

The possibility to employ fuzzy logic when building control systems for dynamic objects, as well as the description of a fuzzy PI-controller and its application to control a steam generator, was reported in [9].

Fuzzy logic in PID-controllers is primarily used in two ways: to build the regulator itself, and to arrange tuning of PID-controller's coefficients.

Implementation of the fuzzy PID-controller may lead to problems because it must have a three-dimensional table of rules in accordance with three setting factors, which is very difficult to fill in, using the knowledge of an expert. In addition, a fuzzy controller is a nonlinear element itself. The introduction of such a unit to the control circuit makes it impossible to apply well-known methods for studying control systems, specifically, the use of frequency characteristics to assess stability factor of the system. Thus, final tuning of a fuzzy controller, which is close to optimal, remains a challenging task [9].

Given the analyzed complexities in implementation, and with a respect to negative impact of D-component on the robustness of a system, we shall subsequently consider the PI-controller.

One of the most common structures of a fuzzy PI-controller is shown in Fig. 1. Inconsistency signal e and derivative of an inconsistency signal de/dt arrive at the input of the controller. First, both magnitudes are processed by the fuzzification operation, then the obtained fuzzy variables are employed in the fuzzy output unit for obtaining the output signal, which, following the defuzzification operation, is sent to the output of the controller as control signal u.

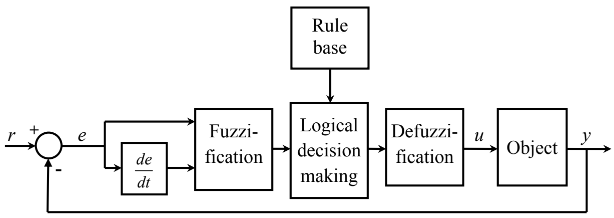

Fig. 1. Structure of fuzzy controller

Under conditions of parametric non-stationarity of CO, variant 2 is especially interesting (Fig. 2), in which a fuzzy controller acts in fact as a unit for the adaptation of coefficients of the primary PI-controller.

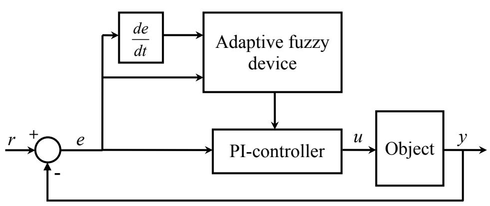

Fig. 2. PI-controller with an adaptive fuzzy-logic device

The absence of the fuzzy logic unit in the main control channel allows us to consider control system at a separate moment of time as a linear one, and thereby apply well-known methods for analysis and synthesis of linear systems, for example frequency characteristics [10].

3. The aim and objectives of the study

The aim of present research is to enhance the quality of automatic control system under conditions of parametric non-stationarity of CO. It is proposed to use the circuit with the principal PI-controller and the unit of adaptation of PI-controller's coefficients based on fuzzy logic.

To accomplish the set goal, the following tasks must be solved:

– to determine the ranges of input and output linguistic variables in the fuzzy adaptive device under conditions of parametric non-stationarity of CO;

– based on the expert knowledge about dynamics of CO, to design a base of rules of the fuzzy adaptive device;

– to perform a comparative analysis of operation of the system that employs classic PI-controller and the system with the fuzzy adaptive device, and to determine quality parameters of control systems.

4. Development of the controller with a fuzzy adaptive device

4. 1. Analysis of ranges for input linguistic variables

When constructing control systems with the use of fuzzy logic-based controllers, it is necessary to take into consideration the following principles:

– using a fuzzy controller does not warrant that the behavior of control system can be predicted in advance with a certain accuracy;

– correct setting of the fuzzy controller is impossible without a prior study into the operation of control system with the PI-controller;

– setting of the fuzzy controller must be based on the observation of operation of CO by one of the channels of control system;

– the operation of control system with a fuzzy controller can warrant the expected control quality only along the channel, which was preliminary used to examine the system's operation. Quality of operation of the control system along other channels is impossible to predict.

Given the specificity of CO (a uniflow boiler), the channel "disturbance–output" was accepted as the principal control channel in present study. The rationale implies that during operational cycle the channel "task–output" is typically used only when driving CO to the assigned operation mode. Operation along the channel "disturbance–output" proceeds for the rest of the time.

As the target system, we have chosen the adaptive control system with a PI-regulator with the fuzzy controller as an adaptive device. It follows hence that even in the case a fuzzy controller fails, or malfunctions, the limitations imposed on the output magnitudes (K_p and T_i) will ensure further correct progress of the transition process, only with worse quality indicators. In the case an intelligent control system is employed, it is not possible to assert confidently that the transition process crosses the stability limit, which is critical for such an important object as a uniflow boiler.

To construct fuzzy controller of a given type, it is necessary to have a certain array of knowledge about operation of the assigned control object. This factor is decisive in the concept of "expert information", that is information, based on which it is possible to design a database of rules.

In terms of knowledge, it is necessary to realize the magnitude of certain criteria during operation of the system. These criteria are nothing short of the input and output parameters of the developed fuzzy controller. Since we previously chose the adaptive control system with the fuzzy adaptive device, the output parameters are the parameters of classic PI-controller – K_p and T_i. As input parameters, different magnitudes can be employed: an error signal, derivative from the error signal, error integral, rate of error integral change, etc. Error signal e and derivative from the error signal de/dt were determined as parameters of the fuzzy controller.

Modeling of the parametric non-stationarity was performed in the form of the variation of values of parameters for a mathematical model of the object within 20 %, which corresponds to the most widespread range of changes in the parameters of heat power equipment.

The course of modeling is as follows:

1) Determining such parameters of the object under conditions of parametric non-stationarity when the transition

process in the system with a classic PI-controller becomes unacceptable for a preset criterion.

2) Assessment of ranges of parameters, which are the input for the fuzzy controller. The obtained data will be used to determine the input linguistic variables of the fuzzy controller.

3) Calculation in line with the procedure of extended amplitude-phase characteristic (EAFC) of parameters of PI-controller for critical states of the mathematical model of an object for a certain criterion. These settings of PI-controller will be used in determining the output linguistic variables of the fuzzy controller.

4) Measurement of ranges of input parameters for the fuzzy controller on transition processes with critical objects and the calculated PI-controller. These ranges will also be used in determining the input linguistic variables of the fuzzy controller.

Table 1 gives data that were derived upon modeling of transition processes under conditions of parametric non-stationarity. A quadratic integral criterion and an attenuation degree were selected as the key criteria.

Transfer function of CO is described by the aperiodic link of the first order with a delay:

$$W_{Ob}(p)=\frac{k}{Tp+1}e^{-\tau p}. \quad (1)$$

Such a notation is inherent for the majority of objects whose dynamics is related to a transfer of any type of energy, specifically thermal. The use of the link of transport delay enables the approximation of models of actual processes that are in reality described by differential equations of higher orders, a link of the first order. At the same time, such an approach to determining the CO model ensures design of the robust system since the process in this case is *a priori* described in a more general form.

Let us consider the system of control over the temperature of live steam in the uniflow boiler assembly TPP-210A. A transfer function of a given circuit at the rated values of model parameters takes the form:

$$W_{Ob}(p)=\frac{4.8}{375p+1}e^{-40p}. \quad (2)$$

Ranges of change in model parameters:

– k – [3.84; 5.76];

– T – [300; 450];

– τ – [32; 48].

Ranges of input parameters of the fuzzy adaptive device are summarized in Table 2.

Based on the results of previous experiments, test modeling and tuning of the final models for the fuzzy controller, the following range was established for the input linguistic variable "error signal" (Fig. 3): [–0.93; 0.35]. For the input linguistic variable "derivative from the error signal" (Fig. 4), the range is [–0.016; 0.0175].

Based on the results of previous experiments, test modeling and tuning of the final models for the fuzzy controller, the following range for the output linguistic variable "K_P coefficient" was established: [0.9; 2.6]. For the output linguistic variable "T_i coefficient", the range is [120; 180].

The breakdown of variables was determined empirically. The result is shown in Fig. 5 (for K_P coefficient) and Fig. 6 (for T_i coefficient).

Table 1

Data of transient processes modeling under conditions of parametric non-stationarity

No.	k	T	τ	attenuation degree	quadratic integral criterion
1	4.8	375	40	0.925	43.72
2	4.8	450	40	1	40.75
3	**4.8**	**300**	**40**	**0.8**	**50.93**
4	**4.8**	**375**	**48**	**0.8**	**60.2**
5	4.8	375	32	1	35.53
6	4.8	450	48	0.89	51.59
7	4.8	300	32	0.89	37.77
8	4..8	450	32	1	34.4
9	**4.8**	**300**	**48**	**0.57**	**90.59**
10	5.76	375	40	0.82	51.65
11	3.84	375	40	1	38.18
12	5.76	450	40	0.92	45.6
13	**5.76**	**300**	**40**	**0.61**	**72.29**
14	.3.84	450	40	1	36.68
15	3.84	300	40	0.93	41.18
16	**5.76**	**375**	**48**	**0.59**	**89.77**
17	5.76	375	32	0.92	38.58
18	3.84	375	48	0.93	47
19	3.84	375	32	1	32.72
20	**5.76**	**450**	**48**	**0.78**	**64.15**
21	**5.76**	**300**	**48**	**System is not stable**	**281.9**
22	3.84	450	48	0.98	43.55
23	3.84	300	48	0.81	55.13
24	5.76	450	32	1	36.7
25	5.76	300	32	0.81	42.87
26	3.84	450	32	1	32.07
27	3.84	300	32	1	33.9

Table 2

Ranges of input parameters of the fuzzy controller

No.	K	T	τ	e min	e_max	de/dt_min	de/dt_max
16	5.76	375	48	–1.013	0.104	–0.0154	0.0105
20	5.76	450	48	–0.865	0.09	–0.0128	0.0089
21	5.76	300	48	–1.223	0.126	–0.0192	0.0129

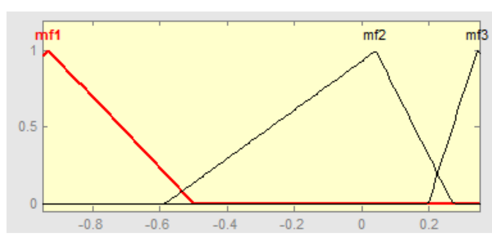

Fig. 3. Terms of the input linguistic variable "error signal"

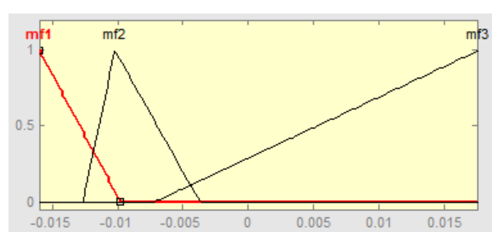

Fig. 4. Terms of the input linguistic variable "derivative from error signal"

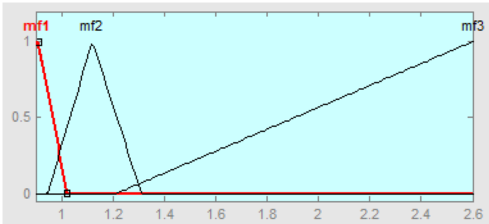

Fig. 5. Terms of the output linguistic variable "K_P coefficient"

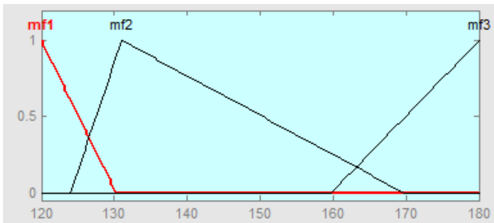

Fig. 6. Terms of the output linguistic variable "T_i coefficient"

The breakdown of variables into terms was performed in order to achieve the following results:

1) Enabling a smooth transition between different terms through partial overlapping.

2) Separation of certain terms to characterize a dimension of the signal error as "principal" (mf1), "close to zero" (mf2), "in re-adjustment region" (mf3); the signal of the derivative from error as "rapidly increasing" (mf1), "slowly increasing" (mf2), and "decreasing" (mf3).

4. 2. Designing a base of rules for the fuzzy adaptive device

Imagine an abstract transition process in a closed single-circuit control system with a PI-controller along the channel "disturbance-output" (Fig. 7).

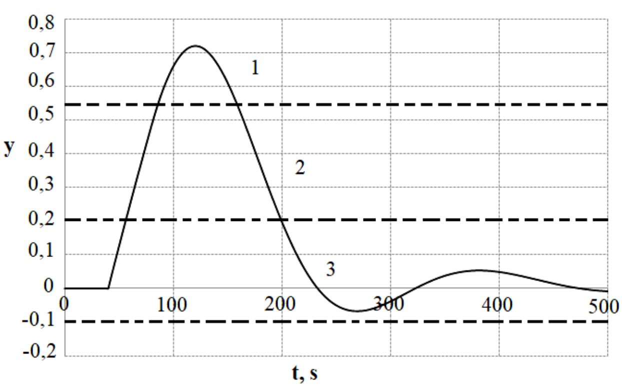

Fig. 7. Graphical representation of rule base on the example of abstract transitive characteristics.
(1: K_P – maximum, T_i – minimum; 2: K_P – minimum, T_i – maximum; 3: K_P, T_i – normal)

Since the control object is characterized by parametrical non-stationarity, it is necessary to develop such a control logic so that it satisfies all states of a given object. For this purpose, it is proposed to take into consideration the following statements:

1) at the very beginning of the transition process, it is necessary to maximize K_P coefficient of the controller, as well as to minimize T_i, coefficient of the controller, which will make it possible to overcome disturbances quickly;

2) at the stage that follows the first cast, it is necessary to minimize K_P coefficient and to maximize T_i coefficient;

3) when the error signal and a derivative from the error signal is close to zero (a process is close to be defined) – to establish K_P and T_i coefficients at the normal level for most states of the object.

Based on the described statements, the base of rules for the PI-controller parameters was designed (Tables 3, 4).

Table 3

Base of rules for controller parameter K_P

e / de/dt	small negative	small	positive
small negative	rated	increased	decreased
small	rated	decreased	decreased
positive	decreased	rated	decreased

Table 4

Base of rules for controller parameter T_i

e / de/dt	small negative	small	positive
small negative	decreased	increased	increased
small	decreased	rated	increased
positive	decreased	decreased	decreased

In order to make it possible to change two parameters of the IP-controller at the same time and independently, two separate databases were built. Input signals of the fuzzy controllers, corresponding to them, are the same – these are error signal e and derivative from error signal de/dt. The output signal of one fuzzy controller is the setting parameter K_P, and of the other – T_i.

5. Results of modeling a system with the fuzzy adaptive device

To construct a fuzzy adaptive device, the MATLAB software package "Fuzzy logic toolbox" was used. The algorithm "mamdani" was employed as a basic fuzzy logic algorithm.

The model of a closed control system with the fuzzy controller created in the Simulink programming environment is shown in Fig. 8.

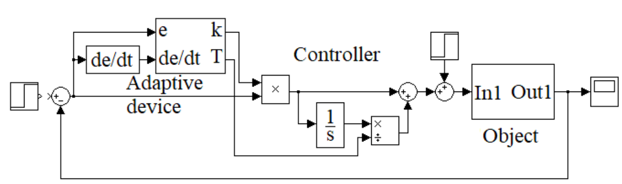

Fig. 8. Model of closed control system with a fuzzy adaptive device

The structure, shown in Fig. 9, is given above as "Adaptive device"

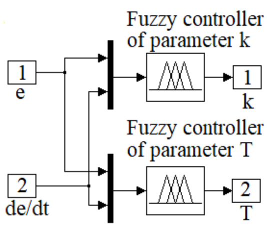

Fig. 9. Structure of the unit "Adaptive device"

Computer simulation of the system with a fuzzy adaptive device was performed for four variants of the state of CO: rated (3), decreased dynamics (4), increased dynamics (5), critically increased dynamics (6):

$$W_{Ob}^{N}(p)=\frac{4.8}{375p+1}e^{-40p}, \quad (3)$$

$$W_{Ob}^{lo}(p)=\frac{3.84}{450p+1}e^{-40p}, \quad (4)$$

$$W_{Ob}^{hi}(p)=\frac{5.76}{300p+1}e^{-40p}, \quad (5)$$

$$W_{Ob}^{hi}(p)=\frac{5.76}{300p+1}e^{-48p}. \quad (6)$$

Fig. 10–13 show transition processes in the system for different states of CO.

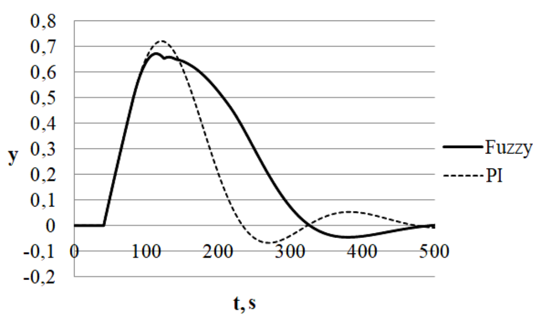

Fig. 10. Transition process at the rated parameters of CO

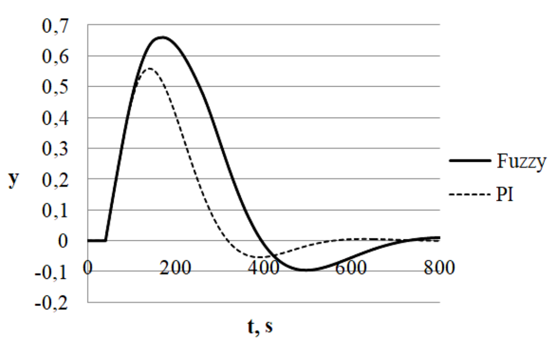

Fig. 11. Transition process at the decreased dynamics of CO

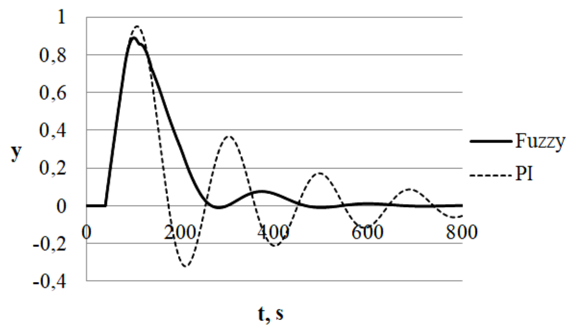

Fig. 12. Transition process at the increased dynamics of CO

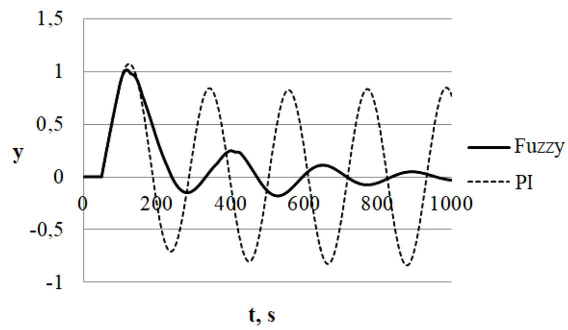

Fig. 13. Transition process at the critical dynamics of CO

Table 5

Quality indicators of system's operation for different states of CO

Quality indicators	Rated		Increased dynamics		Critical dynamics		Decreased dynamics	
	PI	Adaptive fuzzy	PI	Adaptive fuzzy	PI	Adaptive fuzzy	PI	Adaptive fuzzy
Static error	0	0	0	0	System is not stable	0	0	0
Maximum dynamic cast	0.72	0.67	0.931	0.889	System is not stable	1.01	0.555	0.65
Attenuation degree	1	1	0.66	0.91	System is not stable	0.75	1	1
Controlling time	420	320	800	370	System is not stable	700	490	680
Quadratic integral criterion	43.72	48.06	72.29	47.47	System is not stable	81.32	36.68	71.96
Readjustment	–	–	32	0	System is not stable	15	–	–

Table 5 gives quality indicators of the system's operation for different states of CO.

An analysis was carried out by comparing transient characteristics of target control systems under conditions of parametric non-stationarity. The parametric non-stationarity was modeled by changing the parameters of control object within 20 percent.

When analyzing behavior of the control system along the channel "disturbance–output" at the initial state of the control object, it is possible to see that the control system with the fuzzy adaptive device operates worse than the control system with a classic PI-controller. However, this is not a final conclusion about operation of the system under conditions of parametric non-stationarity.

As the presented transitions processes show, an increase in the dynamics of control object (an increase in transfer coefficient k and a decrease in time constant T) leads to compromised stability of the process in the classic system. Specifically, control time increases while the attenuation degree decreases. The base of rules for a fuzzy device is designed so that controller's coefficient K_P decreases to the magnitude that was previously determined when studying control system's operation. This leads to a decrease in the oscillatory characteristics.

A critical state of the control object is achieved by increasing the time of net transportation delay, a decrease in the amplification coefficient and a decrease in the time constant. In this case, the transition process in a classic single-circuit control system with a PI-controller becomes divergent. A controller with the fuzzy adaptive device successfully copes with this deterioration while a given control system remains stable.

Improvement of the state of control object for regulation at constant PI-controller means a decrease in its amplification coefficient and an increase in inertia. This is explained by the fact that the PI-controller, designed for the facility with a lower inertia, can effectively overcome disturbances in a control system. However, specificity of the developed base of rules for the fuzzy controller in this particular case does not contribute to the improvement of regulation quality. At a decrease in the controller's coefficient K_P and at an increase in T_i, the rate of regulation decreases, which leads to an increase in the value of quadratic integral criterion. But in this case the transition process will definitely converge at sufficient rate.

6. Discussion of results of research into automatic control system with a fuzzy adaptive device

As a result of comparative analysis, it can be argued that a single-circuit control system with the fuzzy adaptive device works better than a classic control system with PI-controllers under conditions of parametric non-stationarity. Such a conclusion was drawn based on the fact that the fuzzy controller is faster in overcoming disturbances in a control system in cases when oscillatory capacity of the control object increases. This property makes the control system several times as fast, as well as decreases maximum dynamic cast. Under especially critical conditions, the fixed setting of PI-controllers can lead to the fact that a control system becomes unstable. The proposed technique for setting a fuzzy adaptive device involves a decrease in amplification coefficient and an increase in time constant of the PI-law in situations when an error signal and derivative from the error signal are close to zero (along the channel "disturbance–output"). This reduces oscillatory capacity of a system and helps to keep it stable at much more critical states of the object than the studied ones.

A negative aspect of using the fuzzy adaptive device is its slow response in case of improvement of a control object for regulation in comparison with the classic control system. However, this feature is not worse than the drawback of the classic system under conditions of an increase in oscillatory capacity of an object, as in this case the system remains stable.

Although results of the conducted research are positive, it is necessary to design a control system with the use of the fuzzy controller in minute details, especially if a control object is such an important installation as a uniflow boiler. This is due to the fact that the fuzzy controller produces an output signal based on optional parameters (in this case, an error signal and derivative from the error signal), which are capable of changing uncontrollably. The cause of these changes may be the factors that are not taken into account in designing the base of rules. Due to this, the situation may occur when behavior of a control system will be impossible to predict, which is unacceptable for a facility at an important enterprise.

7. Conclusions

1. Based on the calculated settings of PI-controllers for two different states of CO, the ranges of input and output signals of the fuzzy adaptive device were determined. Settings for different states of CO, calculated in advance, ensure stability of the system under conditions of non-stationarity of the CO model parameters.

2. Based on the knowledge about CO dynamics and possible changes in the parameters of its model, the base of rules for the unit of logical output of the fuzzy adaptive device was developed. For the possibility of simultaneous correction of two parameters of the PI-controller, two separate fuzzy controllers were applied.

3. Comparative analysis revealed that the single-circuit ACS with the fuzzy adaptive device is better suited to the operation with CO, which is characterized by parametrical non-stationarity. Such a conclusion can be drawn by analyzing quality indicators of transition processes in the target ACS at different states of a control object. At increased dynamics of a control object, the fuzzy controller faster overcomes disturbances in CS, direct performance indicators are significantly better than those in the system with a classic PI-controller.

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SYNTHESIS OF ROBUST CONTROLLERS FOR THE CONTROL SYSTEMS OF TECHNOLOGICAL UNITS AT IRON ORE PROCESSING PLANTS

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Для керування процесами збагачувального виробництва в умовах зміни параметрів технологічних агрегатів, як об'єктів керування, досліджено можливість застосування робастних регуляторів. Встановлено, що за показниками номінальної і робастної якості керування доцільним є застосування робастного μ-регулятора, для зниження порядку якого виконано апроксимація з застосуванням Ганкелевої норми

Ключові слова: робастний регулятор, автоматизоване керування, збагачення руди, субоптимальний регулятор, частотні характеристики

Для управления процессами обогатительного производства в условиях изменения параметров технологических агрегатов, как объектов управления, исследована возможность применения робастных регуляторов. Установлено, что по показателям номинального и робастного качества управления целесообразно применение робастного μ-регулятора для понижения порядка которого выполнен аппроксимация с применением Ганкелевой нормы

Ключевые слова: робастный регулятор, автоматизированное управление, обогащения руды, субоптимальный регулятор, частотные характеристики

1. Introduction

Mining-metallurgical complex of Ukraine is one iron ore processing plant of the most important sectors of national industrial production. Specifically, export of ferrous metals, as well as the articles made of them, accounts for almost a quarter of the total value of the exported products. However, over the past decades, changes in the quality of iron ore raw materials have demonstrated a negative trend, which negatively affects product competitiveness of Ukrainian enterprises in the international market. At the same time, still unresolved is the problem on improving energy efficiency of technological processes at mining enterprises.

Numerous studies have proven that the most promising approach to increasing the efficiency of technological processes of the enrichment of iron ore raw materials is the comprehensive automation of control processes. That is, automation systems must engage both separate units, stages, cycles, and the entire production line or an enterprise [1, 2].

When automating control processes of the enrichment of iron ore raw materials, represented by various mineralogical-technological varieties, it is necessary to solve a task on the operational tracking of changes in the condition of control objects and to promptly bring the system to the state of dynamic equilibrium. The biggest changes in the process of enriching the iron ore raw materials happen to granulo-

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