Для оптимізації якості перехідних процесів на нагрівальному об'єкті управління пропонується застосувати нейросетевой настроювач, що змінює параметри ПІ-регулятора в реальному масштабі часу. Метою дослідження є визначення ефективності застосування настроювача на моделі нагрівальної печі, що містить контур управління подачею газу і виконавчий механізм даного контуру. Підтверджується здатність пропонованої адаптивної системи ефективно проводити адаптацію параметрів регулятора при наявності виконавчого механізму, динаміка якого може негативно впливати на якість управління

Ключові слова: ПІ-регулятор, рівноваги вплив, нейросетевой настроювач, адаптивне управління, нагрівальні печі

Для оптимизации качества переходных процессов на нагревательном объекте управления предлагается применить нейросетевой настройщик, изменяющий параметры ПИ-регулятора в реальном масштабе времени. Целью исследования является определение эффективности применения настройщика на модели нагревательной печи, содержащей контур управления подачей газа и исполнительный механизм данного контура. Подтверждается способность предлагаемой адаптивной системы эффективно производить адаптацию параметров регулятора при наличии исполнительного механизма, динамика которого может негативно влиять на качество управления

Ключевые слова: ПИ-регулятор, возмущающее воздействие, нейросетевой настройщик, адаптивное управление, нагревательные печи

APPLYING A NEURAL TUNER OF THE PI-CONTROLLER PARAMETERS TO CONTROL GAS HEATING FURNACES

Y. Eremenko
Doctor of Technical Sciences, Professor*
E-mail: erem49@mail.ru
A. Glushchenko
PhD, Associate Professor*
E-mail: strondutt@mail.ru
A. Fomin
Postgraduate student*
*Department of automation and
information technologies
Stary Oskol Technological Institute named
after A. A. Ugarov (branch of National
University of Science and Technology «MISIS»)
Makarenko str., 42, Stariy Oskol,
Russian Federation, 309516

1. Introduction

The present stage of development of automated systems and control devices is characterized by active modernization of tools for automation and measurements. New devices and means of automation possess high accuracy, wide scope of application, self-adjustment and self-calibration algorithms. Microcontroller equipment has also been actively developed, its reliability improves and computing power increases. However, such a development is levelled off by employing control algorithms that have been applied for quite a long time – more than 90 % of industrial objects of control (OC) are run using a classical PID-algorithm [1, 2].

A controller that implements a given algorithm is linear, while the real objects of control, such as heating furnaces, widespread in the industry, are in most cases essentially nonlinear [3]. The approximation of a nonlinear function (non-linearity) of the object of control by a linear function of the PID algorithm leads to a decrease in the quality of control, overconsumption of energy, and, in some cases, to defects in products. Therefore, it is an important task to build a control system that would be capable of taking into consideration the non-linearity of the object of control.

2. Literature review and problem statement

One of the ways to solve a given problem is to use the classical optimal [4, 5] and adaptive [6, 7] control systems. Their application, however, is related to certain difficulties. The effective use of such systems requires a reliable mathematical model of the object of control, which necessitates an identification procedure. In this case, under industrial conditions, it is rather difficult to perform the procedure of identification of thermal objects. It is possible only when a heating furnace is not loaded or is idle. Identification by methods that employ testing control actions can disrupt technological process and lead to defects, which does not make it possible to perform it on running equipment.

Most often, a possibility for the identification appears when a repair is finished or when a heating furnace is not used.

Another option to solve a given problem is to move away from close connection with the model of control object. Such a possibility is provided by intelligent adaptive control methods, which make it possible, to a certain degree, to simulate human behavior, in particular, expert systems (ES) [8], fuzzy logic [9, 10], neural networks [11–13]. One of the disadvantages of expert systems methods [8] is the absence of possibility of rapid learning, due to the high complexity

of initial formalization of the knowledge of an expert about nonlinearity and peculiarities of the controlled object. Information on any changes in the object of control must be entered to ES manually, during work, the result of which is the relevance of ES only for one particular state of the object of control.

Among the studies that investigate a fuzzy logic apparatus in order to configure settings of the controller, we can highlight those that address configuration of parameters of the controller [9, 10]. The main drawback of the proposed solution is the implementation of method with specific values of coefficients of normalization for the inputs and outputs of the tuner. When changing a control object or at a significant change in the state of the current one, it is necessary to select anew the values of such coefficients.

We shall also consider a neural network apparatus (NN) since NN possesses properties of nonlinearity and capability to operational learning. That is why applying NN renders adaptive properties to control systems. One of such solutions is the circuit for neural-network configuration of a PID-controller proposed by Sigeru Omatu in [12]. The advantage of the given solution is the superstructure character of the adaptation system, which greatly facilitates its integration into existing control contours, taking into consideration nonlinearity of the object of control. The application of S. Omatu scheme is described in papers of many scientists and developers [11, 13]; the solutions obtained, however, are not universal. Their successful application requires significant modification for a specific task and the object of control.

Interest in using these methods is explained by the fact that controllers are set by an ACS TP engineer based on own knowledge, practice, and without employing models.

Analysis of intelligent methods makes it possible to choose a direction in building the systems for automated operational tuning of PI-controllers parameters based on the joint use of the apparatus of expert systems and neural networks. The choice of the PI-controller is predetermined by its wide application at thermal objects of control.

This solution will make it possible, by using ES, to account for the specificity of control object (such as the impossibility of forced furnace cooling), while applying an apparatus of NN would allow the system to learn during operation.

Such an intelligent system is a neural network tuner of PI-controllers' parameters [14]. This development has led to an improvement in energy efficiency of furnace operation under transient modes and perturbation working out. Practical implementation also made it possible to perform a field experiment at a laboratory muffle furnace, where the neuro-tuner proved its effectiveness. However, when constructing a model of the heating furnace, which was used for modeling and for full-scale experiments, the influence of the controlling element was not taken into consideration. The reason for it was that the electric heating muffle furnace was investigated, where a controlling element is the triac whose time constant is too small to influence the results obtained. In reality, however, industrial furnaces, in most cases, are of the gas type, and controlling element is the gas supply valve whose time constant affects control process, which requires its inclusion in the model. That is why the purpose of present study is the operability testing of a neural-network tuner on the model of a heating furnace, taking into consideration influence of the controlling element.

3. The aim and objectives of the study

The aim of present work is to explore the possibility and effectiveness of using a neural-network tuner on the model of a heating furnace that includes a gas flow control circuit.

To accomplish the set aim, the following tasks have been identified:

– to recalculate the model of electrical heating furnace model for a gas furnace, similar in capacity, containing a gas flow control circuit;

– to compare the effectiveness of using a neural-network tuner with a PI-controller within the framework of model experiment.

4. Problem statement and tuner description

A neural-network tuner consists of two subsystems: a neural network and the rule base. The function of rule base is to determine the moments at which it is required to tune a specific channel of the controller. A rule base in essence is the formalized description of empirical rules that allow an ACS TP engineer to tune a controller. As an example, we shall consider a situation that occurs at heating objects of control: an operator, in line with technology, changed a temperature setpoint. In this case, a heating technological card assigns a range of heating rates. A rule base, by monitoring the current heating rate and by comparing it to the technologically required, determines a point in time and a coefficient of the controller, which must be set to maintain the rate in a given range (Fig. 1).

The rule base [14] contains information about 15 different situations (combinations of values for readjustment, static error, self-oscillation, etc.) that may occur during processes of heating, cooling, and under the action of perturbing influences on the system. The task of a neural network is the numerical changing of controller parameters.

Three sets of weight coefficients and offsets are implemented in a neural network, which makes it possible to determine the optimal coefficients (in terms of the required quality of transient processes) for each of the thermal processes: heating, cooling, and compensation for perturbing influences. The need for three sets of coefficients is explained by the different character of nonlinearity in a control object during heating and cooling. Functioning on one set of scale leads to the selection of non-optimal parameters and the deterioration in a transition process [15].

Functional diagram of the obtained system is shown in Fig. 2.

A neural network used in the structure of neural-network tuner represents a three-layer network of direct propagation of signal whose selection is described in detail in [15]. The input layer is represented by four neurons that receive: temperature setpoint, averaged output of the control object, delayed by 1 s, Δt, and output from a PI-controller. Calculation of Δt coefficient was performed according to [15]. In the experiment described in the paper, we used value Δt=20 s. The hidden layer contains 12 neurons with sigmoidal activation functions. The output layer contains two neurons with linear functions of activation whose outputs are coefficients K_P and K_I. The network is trained using an error back propagation method [12].
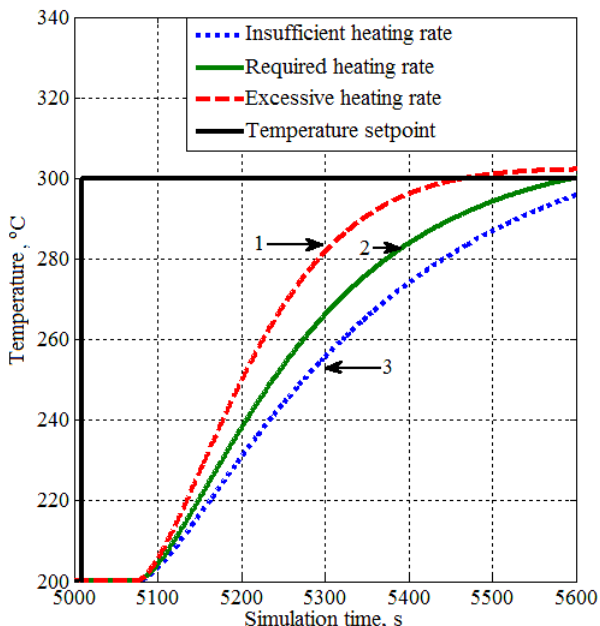
Fig. 1. Example of a situation requiring the intervention of adaptive control system (1 — excessive rate, decrease in K_P, 2 — required rate, 3 — insufficient rate, increase in K_P)
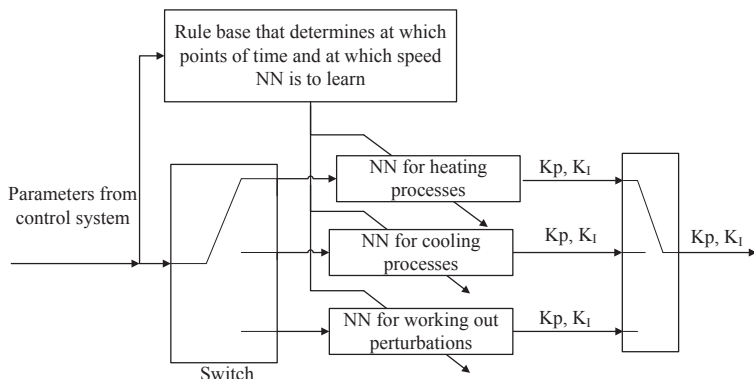

Fig. 2. Functional diagram of a neural-network tuner

Further objective was to study the work of a neural-network tuner on the model of a thermal object that contains internal gas flow control circuit (gas circuit).

5. Application of a neural-network tuner on the model of gas furnace with a gas circuit

To conduct experiment, we employed a complex of software, represented by the following systems – Matlab (modeling of the object of control), Step7, based on which, using the controller simulator S7-400, we implemented a neural-network tuner and a PI-controller, and SCADA system WinCC, which, in addition to the function of visualization, served as a communication connector between Matlab and Step7. Much of the previous research by authors of the present study [14–16] was conducted for the model of muffle furnace SNOL 1,6.2,5.1/11-I, shown as (1).

$$W(s) = \frac{K}{T_1 S + 1} \cdot \frac{1}{T_2 S + 1} \cdot e^{-ts}, \qquad (1)$$

where T_1=1,636 s, T_2=69.8 s, t=63.8 s, K=20.72.

In the present experiment, given that the model of muffle furnace is a model of a typical thermal object [17], it is proposed to accept this model as a model of the gas heating furnace. In this case, we add a gas circuit to it and recalculate it with respect to amplification factor of the object of control. Structural diagram of the model obtained is shown in Fig. 3.

We shall briefly describe a modeling scheme: controlling influence $U(0\div100\,\%)$ arrives from unit *OPC-Read*1 from the PI-controller Simatic. Next, controlling influence is multiplied by factor *F*. This product represents a task for the gas flow control circuit.
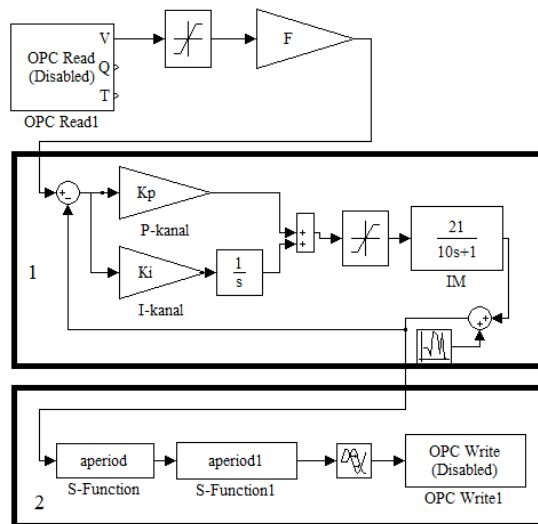

Fig. 3. Structural scheme for modeling a gas furnace (1 — gas circuit, 2 — object of control)

To obtain this factor, we performed calculation in order to convert thermal power of the heating electrical element of a muffle furnace into an analogue for gas furnaces. Electric power of the furnace SNOL is 2.1 kW·h. We shall derive maximal gas consumption per hour from formula (2):

$$F_{max} = \frac{P_{max}}{8.6} = \frac{2.1}{8.6} = 0.244 \ \text{m}^3/\text{hour}, \qquad (2)$$

$$F = \frac{F_{max}}{100\,\%} = 0.00244 \ \text{m}^3/\text{hour}.$$

Next, the task for gas is compared with the actual consumption, an error is calculated, and it is given to the PI-controller of the gas circuit. Because of the high speed of the gas flow meter, its time constant is proposed to be neglected. Parameters for the PI-controller (K_P, K_I) of a gas circuit were chosen empirically to ensure sufficient performance speed and stability of furnace operation mode. The output of gas PI-controller ($0\div100\,\%$ open) is fed to the controlling element (gas valve actuator) whose output is gas consumption. The actuator's parameters are taken from the documentation on the drive Bernard-GAM. This drive is widespread at the enterprises in metallurgical industry and represents a medium-speed drive. Its opening time is t_{tr}=40 seconds. We shall derive a time constant of the drive from equation (3):

$$T = \frac{t_{tr}}{(3+5)/2} = \frac{40}{4} = 10 \text{ s.} \qquad (3)$$

Next, the resulting gas consumption is sent to the model of control object (1), units *S-Function*, *S-Function*1, *Transport Delay*3, whose output is temperature, which via the unit *OPC_write*1 is sent to WinCC, and from there to Simatic to the PI-controller. Gain factor of the control object was recalculated based on the maximum gas flow rate (0.244 m³/h) and the initial furnace gain factor K=20.72 (4):

$$K = \frac{20.72 \cdot 100}{0.244} = 8491.8. \qquad (4)$$

Such a significant gain factor is explained by technical features of the furnace and the method of its recalculation into the gas furnace – with respect to high calorific value of gas, small working volume of the furnace (10 liters) and its power (2.1 kW·h), to achieve the required temperatures for a rather small amount of gas. In this case, maximum furnace temperature is high, which leads to a significant gain factor.

The adaptation system executed the following schedule of temperature setpoints: 505 °C – 550 °C – 630 °C. A transition process was considered completed when finding an error module for temperature in a 5 % range of difference between current and previous temperature setpoints over 300 seconds. Upon completion of the transitional process, a temperature setpoint changed. A cascade of temperature setpoints was repeated 3 times, followed by a change in the parameters of the control object, which simulates loading a piecework into the furnace (K=K–0.2·K, T_1=T_1+1000 s). Following a 4-time work of temperature setpoint cascade, parameters of the model returned to the initial parameters, and a temperature setpoint schedule was repeated 4 more times.

The aim of the experiment is to confirm the operability of a tuner when working with a furnace model, containing a gas flow control circuit. As a result, we obtained charts, shown in Fig. 4, 5.
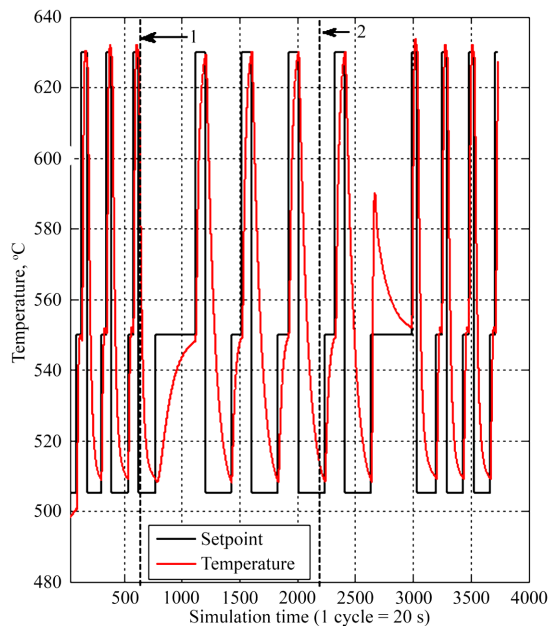

Fig. 4. Transition processes on the model of control object with a gas circuit under control of a neural-network tuner (1 — change in the state of control object, 2 — return to original settings)

Initial settings of the controller are chosen empirically for an empty furnace and ensure the following quality of control: absence of oscillations, readjustment and a static error not exceeding 5 %. These coefficients are starting for neural-network tuner and primary for the PI-controller: K_P=0.45, T_I=2500 s.

Fig. 4, 5 show that the neural-network tuner functions successfully on the model of a heating furnace with a gas circuit. It effectively responds to a change in the state of a control object, and makes it possible to reduce time of transition processes. Table 1 gives comparative characteristics of two experiments.
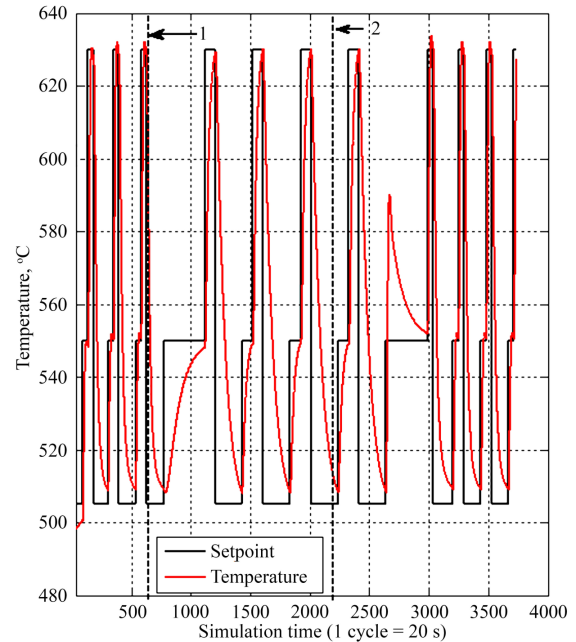

Fig. 5. Transition processes on the model of a control object with a gas circuit under control of the PI-controller (1 — change in the state of control object, 2 — return to original settings)

Table 1

Comparative characteristics of using a neural-network tuner and a PI-controller

Estimation criterion	PI+NN	PI
Experiment duration, hours	14.4	19.4
Time saving, %	25.8	0
Total controlling influence (100), units	13,743	17,815
Saved for total controlling influence, %	22.85	0

Within the framework of previous studies [14 16], a similar experiment was carried out on the same model of the furnace, without taking into consideration a gas circuit. In that case, using a neural-network tuner, we saved 13 % of the transition processes time and 16 % of the control influence.

Research results allow us to draw a conclusion about effective work of the neural-network tuner on the model of a heating furnace with a gas circuit. In this case, the ratios, used in the simulation, of time constants of the furnace and the controlling element are common for the metallurgical industry.

6. Discussion of results of the study into using a neural-network tuner for the PI-controller on the model of a gas furnace

The main advantage of using a neural-network tuner is accounting for thermal-technological characteristics of the controlled objects (employing a rule base) and accounting for their changes under operational mode (applying a neural network). Within the framework of present study we examined the feasibility and effectiveness of control when using a neural-network tuner on the model of a gas furnace.

One drawback of the study is a rather conditional recalculation of the model of an electric furnace into a gas furnace, based on the recalculation of thermal capacity. In addition, the designed variant of the tuner can function effectively only at a stepwise change in the job in control system.

The result of research makes it possible to extend the class of control objects to which a neural-network tuner can be applied. Previously, it was used only for electric furnaces where influence of the controlling element is minimal. Result of the present study makes it possible to scale up the solution for gas thermal furnaces, notwithstanding a markedly larger impact of the controlling mechanism. Application of a tuner makes it possible to improve quality of control over temperature at a thermal object, which has a positive effect on energy efficiency.

Present study is continuation of a larger study into development and application of a neural-network tuner [14–16].

Our further aim is to study the interzone influence of multizone furnaces for taking it into consideration in a rule base of the tuner.

7. Conclusions

1. We devised a model of the gas heating furnace using the recalculation of thermal power of the electric furnace. Its special feature is the presence of a gas supply control circuit, which makes it possible to simulate behavior of actual industrial gas furnaces.

2. The obtained model allowed us to examine the possibility of applying a neural-network tuner for the PI-controller parameters at an object that contains an internal circuit to control gas supply. The result of applying the tuner is a decrease in the time of the transition process by 25.8 % and a reduction of the total controlling influence by 22.85 %. The presence of the controlling element in this case had no significant effect on the work of a neural-network tuner.

References

1. PID Control in the Third Millennium. Lessons Learned and New Approaches [Text] / R. Vilanova, A. Visioli (Eds.). – Springer, 2012. – 599 p. doi: 10.1007/978-1-4471-2425-2

2. Åström, K. J. Automatic tuning and adaptation for PID controllers – a survey [Text] / K. J. Åström, T. Hägglund, C. C. Hang, W. K. Ho // Control Engineering Practice. – 1993. – Vol. 1, Issue 4. – P. 699–714. doi: 10.1016/0967-0661(93)91394-c

3. Mimura, K. Experimental study of PID auto-tuning for unsymmetrical processes [Text] / K. Mimura, T. Shiotsuki // Proceedings of ICCAS-SICE 2009. – 2009. – P. 2967–2971.

4. Salikhov, Z. G. Modeling of Singularly Perturbed multi-criterion Optimal Control Workflows [Text] / Z. G. Salikhov // IFAC-PapersOnLine. – 2015. – Vol. 48, Issue 3. – P. 1254–1258. doi: 10.1016/j.ifacol.2015.06.256

5. Athans, M. Optimal control: an introduction to the theory and its applications [Text] / M. Athans, P. L. Falb. – Dover Publication, 2007. – 879 p.

6. Alexandrov, A. G. Adaptive PID controllers: State of the art and development prospects [Text] / A. G. Alexandrov, M. V. Palenov // Automation and Remote Control. – 2014. – Vol. 75, Issue 2. – P. 188–199. doi: 10.1134/s0005117914020027

7. Mahmoodabadi, M. J. Adaptive robust PID control subject to supervisory decoupled sliding mode control based upon genetic algorithm optimization [Text] / M. J. Mahmoodabadi, M. Taherkhorsandi, M. Talebipour, K. K. Castillo-Villar // Transactions of the Institute of Measurement and Control. – 2014. – Vol. 37, Issue 4. – P. 505–514. doi: 10.1177/0142331214543295

8. Calvo-Rolle, J. L. A hybrid intelligent system for PID controller using in a steel rolling process [Text] / J. L. Calvo-Rolle, J. L. Casteleiro-Roca, H. Quinti n, M. del Carmen Meizoso-Lopez // Expert Systems with Applications. – 2013. – Vol. 40, Issue 13. – P. 5188–5196. doi: 10.1016/j.eswa.2013.03.013

9. Ferdiansyah, I. Fuzzy Gain Scheduling of PID (FGS-PID) for Speed Control Three Phase Induction Motor Based on Indirect Field Oriented Control (IFOC) [Text] / I. Ferdiansyah, E. Purwanto, N. A. Windarko // EMITTER International Journal of Engineering Technology. – 2016. – Vol. 4, Issue 2. doi: 10.24003/emitter.v4i2.147

10. Erenoglu, I. An intelligent hybrid fuzzy PID controller [Text] / I. Erenoglu, I. Eksin, E. Yesil, M. Guzelkaya // European Conference on Modelling and Simulation. – Bonn, 2006. – P. 62–66. doi: 10.7148/2006-0062

11. Hornik, K. Multilayer feedforward networks are universal approximators [Text] / K. Hornik, M. Stinchcombe, H. White // Neural Networks. – 1989. – Vol. 2, Issue 5. – P. 359–366. doi: 10.1016/0893-6080(89)90020-8

12. Omatu, S. Neuro-Control and its Applications [Text] / S. Omatu, M. Khalid, R. Yusof. – Springer, 1996. – 255 p. doi: 10.1007/978-1-4471-3058-1

13. Fang, M.-C. The application of the self-tuning neural network PID controller on the ship roll reduction in random waves [Text] / M.-C. Fang, Y.-Z. Zhuo, Z.-Y. Lee // Ocean Engineering. – 2010. – Vol. 37, Issue 7. – P. 529–538. doi: 10.1016/j.oceaneng.2010.02.013

14. Eremenko, Y. I. On development of method to calculate time delay values of neural network input signals to implement PI-controller parameters neural tuner [Text] / Y. I. Eremenko, A. I. Glushchenko, A. V. Fomin // 2016 2nd International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM). – 2016. doi: 10.1109/icieam.2016.7910937

15. Glushchenko, A. I. Neural tuner development method to adjust PI-controller parameters on-line [Text] / A. I. Glushchenko // 2017 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus). – 2017. doi: 10.1109/eiconrus.2017.7910689

16. Eremenko, Y. I. PI-controller parameters tuning method to reject disturbances acting on heating furnaces [Text] / Y. I. Eremenko, A. I. Glushchenko, A. V. Fomin // 2016 2nd International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM). – 2016. doi: 10.1109/icieam.2016.7910910

Проведено аналіз особливостей реалізації комбінованих систем в залежності від способу вмикання компенсатора. Запропоновано спосіб параметричного синтезу цифрових комбінованих автоматичних систем регулювання на основі принципу інваріантності з розрахунком замкненого контуру за методом багатокритеріальної параметричної оптимізації. За розробленим підходом наведено приклад синтезу комбінованої системи з цифровим ПІД-регулятором та реальним об'єктом

Ключові слова: цифрові системи регулювання, комбіновані системи, багатокритеріальний параметричний синтез, ПІД-регулятор

Проведен анализ особенностей реализации комбинированных систем в зависимости от способа включения компенсатора. Предложен способ параметрического синтеза цифровых комбинированных автоматических систем регулирования на основе принципа инвариантности с расчетом замкнутого контура методом многокритериальной параметрической оптимизации. По разработанному подходу приведен пример синтеза комбинированной системы с цифровым ПИД-регулятором и реальным объектом

Ключевые слова: цифровые системы регулирования, комбинированные системы, многокритериальный параметрический синтез, ПИД-регулятор

PARAMETRIC SYNTHESIS OF COMBINED AUTOMATIC REGULATING SYSTEMS WITH DIGITAL PID-CONTROLLERS

I. Kovela
PhD, Associate Professor*
E-mail: ivan.m.kovela@lpnu.ua

O. Ivaniuk
PhD, Senior Lecturer*
E-mail: olegiv.mail@gmail.com

G. Vlakh-Vyhrynovska
PhD, Associate Professor*
E-mail: galinalvov@email.ua

R. Stakhiv
PhD, Associate Professor*
E-mail: ristakhiv@gmail.com

*Department of computerized automation systems
Lviv Polytechnic National University
S. Bandery str., 12, Lviv, Ukraine, 79013

1. Introduction

The overwhelming majority of the industrial facility regulation systems operate on the fundamental principle of deviation. In the practice of automation, such systems account for approximately 85 % [1]. This is explained by the fact that the regulatory action in them is formed regardless of the number, type and place of application of disturbances. In this case, with the help of one regulating action, it is often possible to achieve satisfactory compensation for several disturbances. However, the regulator in such systems begins to form regulating effect to compensate for the disturbance just after emergence of deviation of the regulated value from the specified one. Therefore, it is impossible to completely eliminate discrepancy between the regulated quantity and the task given to the regulator and only minimization of these deviations can be achieved in the systems operating on the basis of deviation.

With this approach, it is far from always possible to provide required quality of regulation if there are delays in the object's regulation channel and significant disturbances. In such cases, systems with a complicated information structure (e.g. cascade systems and systems with dynamic correction) are often found to be effective. However, not all objects have the technical ability to allocate auxiliary regulated values characterized by their delay and inertiality in relation to the principal disturbances of the object and the regulatory action less than the main regulated value. In addition, appearance of additional loops can be a source of a potentially unstable system. At the same time, presence of inertiality and delay in the advance part of the object can result in a loss of any effect from introduction of an additional status variable.