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SELECTING A METHOD FOR THE PARAMETRIC ADAPTATION OF PI-CONTROLLER IN THE CONTROL SYSTEMS OF BOILER ASSEMBLIES AT THERMAL POWER STATIONS WITH SUPERCRITICAL PARAMETERS

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In the context of the growing share of renewable energy sources, the role of thermal power plants (TPPs) as means of balancing the daily power demand curve is increasing. During the day, the load on working units varies widely. Boiler assemblies of these power units undergo changes in their dynamic characteristics when the load changes. Control systems must, regardless of the mode of operation, meet requirements for the quality of operation. This paper has analyzed the latest research and advancements in the field of synthesis of adaptive and robust control systems for inertial contours of direct-flow boiler assemblies. It reports a model of the section of a water-steam flow path, which takes into consideration changes in the dynamic characteristics of the section when changing the load of the power unit. A model of the temperature control system for a boiler assembly has been built involving a tabular method for adjusting the PI-controller parameters. Alternative methods for the adaptation of parameters were proposed. The resulting expressions demonstrate a piecewise-linear approximation of parameter changes depending on the load. In addition, an adaptation unit based on fuzzy logic were suggested. Static characteristics of the adaptation units for PI-controller parameters depending on the load of the power unit were defined. Based on computer modeling, a comparative analysis of the quality indicators of the functioning of the designed control systems was carried out. A method for estimating the stability of systems with adaptation of adjustment parameters was proposed. Based on the static characteristics of the pairs of settings of the PI-controller and the parameters of the control object for each load value at the predefined discreteness, stability reserves were calculated for gain and phase. The results reported here indicate the advantages of a control system with the adaptation of controller parameters based on piecewise-linear dependences

Keywords: PI-controller, adaptation of parameters, tabular control, stability margin, fuzzy logic

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1. Introduction

The world's electricity industry is undergoing a period of transformation from the use of traditional means of electricity generation to renewable energy sources (RES). By 2030, electricity production by wind power plants (WPP) in Europe should reach 14 %; by solar power plants (SPP) – 7 % [1]. Ukraine is also actively implementing RES. From 2017 to 2021, their share in the structure of electricity generation increased from 1.2 % to 8 % [2]. Despite this, the share of coal-fired thermal power plants (TPP) in Ukraine, as well as in the world, remains high. It is projected that by 2040 the share of thermal power plants would remain stable [3]. A decline in TPP electricity production is expected in Europe (by 3.7 %) and China (0.5 %), while its growth is expected in India (3.6 %) and Southeast Asia (4.4 %). The importance of thermal energy in increasing the share of RES is explained by the possibility of balancing daily power daily power demand curve (DPDC) [4]. In 2021, the share of electricity production at thermal power plants in Ukraine amounted to 23.8 %. Further increase in the share of RES is complicated by the lack of maneuverable capacities of the Integrated Power System of Ukraine (IPS), which is overloaded with base capacities (NPP and the majority of TPP power units). Similar problems are faced by the power system of Poland, in which the share of electricity generation by coal-fired thermal power plants reaches 65 % [5]. As a result, TPP power units designed to operate under basic modes are used as maneuverable, a significant part of which operates under non-project peak and semi-peak modes. Under such conditions, the main capacities for regulating the DPDC are power units at thermal power plants of 150, 200, and 300 MW. Therefore, the issue of ensuring stable, reliable, and efficient operation of TPP power units' control systems throughout the entire load change range is relevant.

2. Literature review and problem statement

Studies to improve the efficiency of TPP functioning under maneuvering modes have been carried out since the late 1990s. In 2001, the modernization of power unit No. 2 was completed at Trypilska TPP [6]. In the cited article, its authors described physical processes in the water and steam flow path (WSFP) that cause changes in the dynamic properties of the control object. The main signal in the described control system is the signal for temperature in the ceiling steam heater (CHS). This parameter is characterized by high inertia and time delay. As an advance signal, a signal was classically used for temperature in the upper radiation part (URP). The authors of the cited article proposed a scheme for controlling the temperature regime of a boiler unit with the introduction of an additional differentiator for steam temperature in the lower radiation part (LRP). Thus, two differentiators were formed in a given scheme. That made it possible to reduce the time of transition processes by 25–30 % [6]. Another issue was to ensure both the stability of the control system and the specified quality indicators of the control system within the entire range of load changes. According to the operating staff, that task was solved with the help of tabular control. For a load range of 75–100 %, three pairs of PI controller settings were used. This technique has known drawbacks, so the search for the best solution has been continued. In the first half of the 2010s, much attention was paid to adaptive control systems. In work [7], a method of adaptive adjustment of the PI-controller using a trial harmonic signal was proposed. The method can only be applied in single-circuit control systems for static objects. Another algorithm for setting up an PI-controller, based on the recursive method of the least squares, is described in [8]. The disadvantages include the iterative configuration procedure. Later, the methods of synthesis of robust control systems were developed. In work [9], a two-channel controller with a dynamic corrector was proposed. The control system with this controller provides a given margin of stability throughout the load range. However, as regards the quality of transitional processes, that controller would be inferior to PI controllers configured for specific modes of operation of the control object. In work [10], a controller with an internal model was used. The criterion for optimizing the parameters of adjusting the control unit was H-∞ norm. However, transitional processes in such systems are delayed. Practically, we obtain a controller with a "weak" setting. In fact, this approach to ensure the reliability and stable operation of control systems is very common; the analysis of such systems is set out in article [11]. In it, the author criticizes adaptive control systems. Disappointments from the use of adaptive systems are explained by the inability to conduct active experiments in practice; passive identification in the industry is complicated by unpredictable disturbances, interference with information signals, the stochastic nature of technological parameters with an indefinite distribution [9]. At the same time, papers describing controllers based on fuzzy logic continue to appear, including for thermal energy facilities. In [12], a unit of fuzzy logic is used as a unit for adapting the parameters of the PID controller in the control system of a nonlinear object. Moreover, the adaptation is carried out only for the proportional gain and the integral time constant. The differential component remains stable. A similar version of the controller is considered in article [13]. The adaptation unit in it also works based on fuzzy logic. It demonstrated very good results of functioning and stability of operation under conditions of parametric non-stationarity of the control object. In the absence of an adaptation unit, the control system lost stability while reducing the load of the power unit. In addition to the unit of adaptation of the settings of the PI-controller, fuzzy logic is also used to describe complex nonlinear objects. That approach is employed in work [14] to formalize the process of burning fuel in the furnace of the boiler assembly. Unlike the considered schemes with the adaptation of PI-controller parameters, in [15] two units of fuzzy logic connected in parallel are placed in the direct channel of the control scheme. The knowledge and experience of operator's control are transferred to the database of rules of the so-called two-channel fuzzy controller. The results demonstrate a significantly better reaction of the system with this controller to perturbations compared to even the PID controller. However, the disadvantages of the two-channel controller include a very high complexity in its configuration, as well as a nonlinear nature. At the same time, article [15] shows that a two-channel fuzzy controller can be approximately reduced to an PI controller with an adaptation unit. A common disadvantage of the schemes with fuzzy logic is the use of derivative from the error signal. In practice, for industrial facilities, the use of even the first derivative is significantly complicated by the stochastic nature of the main signal, as well as the presence of interference. The effective use of the derivative to form a control effect requires the application of complex filtration algorithms [16]. Therefore, they are usually limited to the PI controller. No best control system for a nonstationary object could be detected. Each of the schemes has its advantages and disadvantages. A common disadvantage for modern schemes is their complexity. Instead, in the industry, simple and understandable solutions are adopted [11]. In addition to the development of new methods and control schemes, the model of the control object was also improved. Article [17] describes computer models of a steam turbine, the sections of steam heaters of hot steam and heat exchangers of nutrient water depending on the load of the power unit. Paper [18] describes mathematical models in the form of Laplace transfer functions of the water-steam tract in a direct-flow boiler assembly, which take into consideration changes in the dynamic properties of the control object depending on the load. No analysis of the operation of control systems with such a model of the object was carried out before that.

3. The aim and objectives of the study

The purpose of this work is to determine the best method for adapting the parameters of the PI-controller for the control system of the temperature regime in the water steam supply tract of the direct-flow boiler assembly. This will make it possible to improve the quality indicators of transients and, as a result, reduce energy consumption during electricity generation at existing TPP power units.

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

– to derive functional dependences of change in the PI-controller Kp and Ti parameters on the load of the power unit;

– to develop computer models of units for adapting the settings of the PI-controller based on tabular adjustment, a piecewise-linear (PL) dependence, and fuzzy logic, to carry out simulation of the designed control systems within the entire range of load change of the control object;

– to perform a comparative analysis of the quality indicators of transition processes and evaluate the stability reserves of control systems for their quantitative assessment.

4. The study materials and methods

Paper [18] constructs and describes a model for changing the temperature in a WSFP from LRP to the intermediate point after CHS. The simplified scheme is shown in Fig. 1. A given model takes into consideration changes in the dynamic characteristics of the sections of a WSFP of the boiler (LRP, URP, CHS) depending on the load of the power unit. In work [19], an assessment of the adequacy of the built models was carried out according to the Fisher criterion. For all models of the sections of a WSFP, the value of the calculated Fisher criterion was less than the tabular one, therefore the model can be considered adequate.

The control signal u comes from the PI-controller. The temperature regime of the WSFP is maintained by a change in fuel consumption. Load change N is an external disturbance for the system of automatic control (SAC) of the temperature regime. This signal is easy to measure. Knowing the models of the control object at different loads, the authors of [18] derived the functional dependences of the parameters of the transfer functions on the load N in the form of piecewise-linear dependences. The disturbance signal d indicates unpredictable external disturbances that are not measured and are known by changing the output signals of the object y and p. The signal y indicates an inertial signal for the steam temperature according to CHS. The signal p is ahead of the signal y. In addition to the main signal y, it takes into consideration the rate of change in the temperature of the water steam mixture in the areas of LRP and URP. The Laplace formula for calculating the representation of the signal p is as follows:

$$\begin{aligned}P(s)&=W_{CHS}(s)U(s)+\\&+W_{LRP}(s)W_{RD1}(s)U(s)+\\&+W_{VRC}(s)W_{RD2}(s)U(s),\end{aligned} \tag{1}$$

where s is the Laplace operator;

$P(s)$ – representation of the signal p;

$U(s)$ – representation of the control signal u;

$W_{CHS}(s)$ is the transfer function for temperature based on CHS;

$W_{LRP}(s)$ is the transfer function for temperature based on LRP;

$W_{VRC}(s)$ is the transfer function for temperature based on URP;

$W_{RD1}(s)$ is the signal differentiator's transfer function for temperature based on LRP;

$W_{RD2}(s)$ is the signal differentiator's transfer function for temperature based on URP.

In the transfer functions $W_{CHS}(s)$, $W_{LRP}(s)$, $W_{VRC}(s)$, parameters are the functions from the signal N.

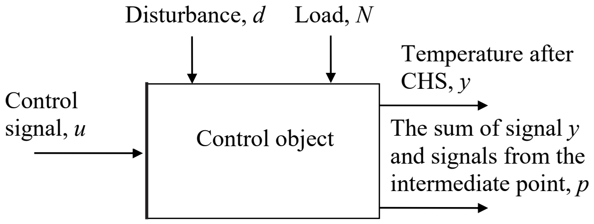
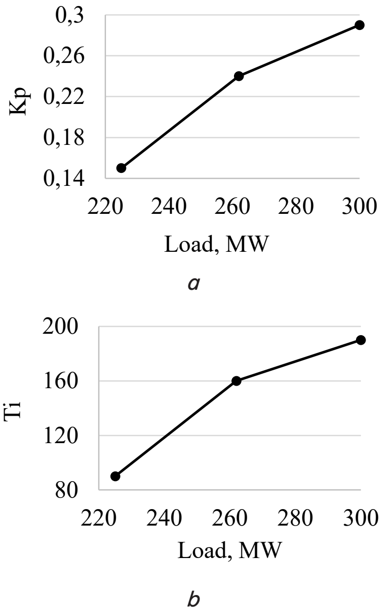


Fig. 1. Control object input and output signals diagram

For different values of load N, the settings for the PI-controller were calculated (Fig. 2). The criterion of calculation was minimization of the dynamic error of the transition process in the absence of overshooting the technological parameter. Fig. 2 shows that the settings of the PI-controller vary nonlinearly depending on the load. This is a consequence of the nonlinear dependence of the parameters of the transfer functions of the corresponding sections of the WSFP on load [19].



a

b

Fig. 2. Setting up the PI-controller depending on the load *N*: *a* — proportional gain; *b* — integral time constant

Hereafter, the range of values is to be indicated not in physical units MW but as a percentage. In this case, a load of 225 MW corresponds to 75 %; 300 MW – 100 %.

5. Results of investigating the functioning of control systems with parametric adaptation of the PI-controller

5. 1. Defining the mathematical dependences of PI-controller settings on the load of the power unit

At tabular control, the control system has three pairs of settings for different load ranges:

$$f_{PI}^{discrete}(Kp,Ti)=\begin{cases}N\in[75\,\%,81\,\%),\,Kp=0.15,\,Ti=90;\\N\in[82\,\%,93\,\%),\,Kp=0.24,\,Ti=160;\\N\in[94\,\%,100\,\%),\,Kp=0.29,\,Ti=190.\end{cases} \tag{2}$$

Switching occurs at the limit of load values of 81–82 % and 93–94 %.

Under the PL method of adaptation, the functional dependences of the parameters of the PI-controller take the following form:

$$f_{PI}^{Linear}(KP,Ti)=\begin{cases}N\in[75\,\%,87.5\,\%),\\Kp=0.15+(N-75)\times0.0072,\\Ti=90+(N-75)\times5.6;\\N\in[87.5\,\%,100\,\%),\\Kp=0.24+(N-87.5)\times0.004,\\Ti=160+(N-87.5)\times2.4.\end{cases} \tag{3}$$

To implement the intermediate option of adapting the parameters of the PI-controller, a unit of fuzzy logic was selected. The input signal is one – load *N*; the output signals are two – Kp and Ti parameters. For each signal, three linguistic variables were defined, denoting a small (LOW), medium (MID), and large (HIGH) signal value (Fig. 3). The base of the rules for the unit of fuzzy logic consists of three rules, respectively, for each linguistic variable of the signal by load.

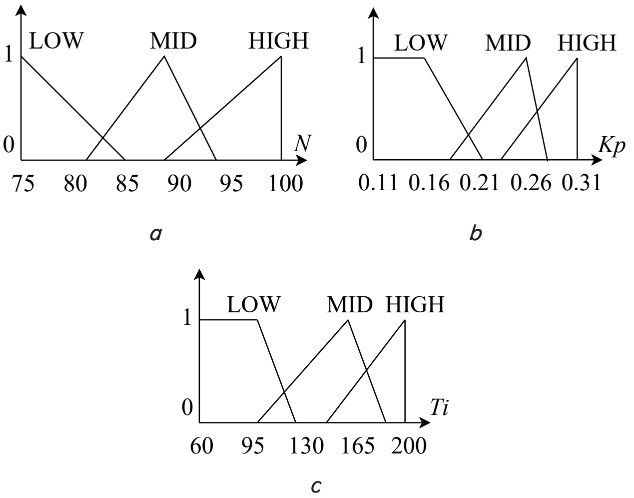


Fig. 3. Adjusting the fuzzy adaptation unit: *a* — input variable *N;* *b* — output variable *Kp; c* — output variable *Ti*

The calculation of output signals is carried out according to the Mamdani algorithm. Mamdani's algorithm is chosen as a fuzzy output algorithm since it allows the use of linguistic variables to form a decision, and the justification for making a decision according to the Mamdani algorithm is more transparent. Sugeno's fuzzy output algorithm is more expedient to use in identification problems. Based on the developed membership functions and the base of rules, static characteristics are obtained for the Kp and Ti parameters for each load value.

The implementation of a fuzzy adaptation unit on industrial automation tools is possible based on modern programmable logic controllers (PLCs) that support the Structured Text (ST) language of the IEC 61131-3 standard. There is the IEC 61131-7 standard, which describes the Fuzzy Control Language (FCL) for representing fuzzy models of control systems, in particular for PLCs, in the form of structured text, which can be interpreted as a program in a high-level language. However, the IEC 61131-7 standard is not implemented in modern PLCs, unlike the IEC 61131-3 standard. Work [19] implemented units of fuzzy derivation according to the algorithm by Mamdani in the ST language based on PLC AXC F 2152 generation PLCnext Technology by Phoenix Contact. The Works Engineer 7.2.3 software is used for programming.

The comparison of static characteristics of adaptation of parameters of the PI-controller depending on the load *N* is shown in Fig. 4.

In Fig. 4, the plots of PL dependences repeat the characteristics shown in Fig. 2. For the tabular method of setting with an average load level, they occupy 50 % of the range of the scale *N*. The settings for the minimum and maximum load occupy 25 % of the scale. The static characteristic for the fuzzy method is significantly nonlinear throughout the load range.

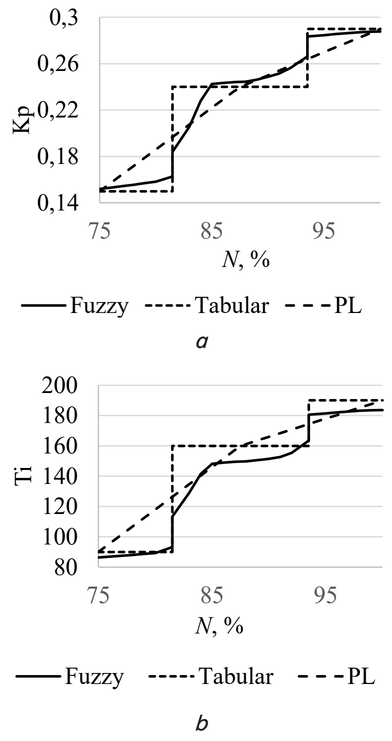


Fig. 4. Comparing the static characteristics of PI-controller settings depending on the load *N: a* — proportional gain; *b* — integral time constant

5. 2. Constructing simulation models of control systems with parametric adaptation of the PI-controller

Fig. 5 shows a diagram of the control system with tabular adjusting of the parameters of the PI-controller. For a temperature regime SAC, the main task is to compensate for disturbances. Therefore, hereafter only transitional processes in compensation of disturbance are considered.

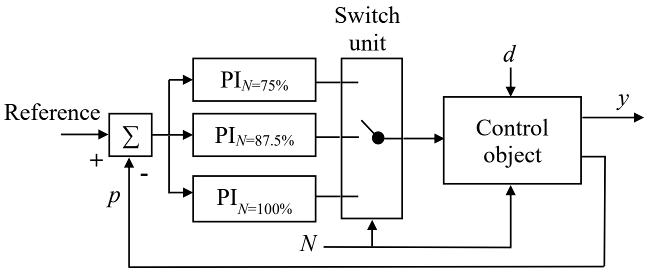


Fig. 5. Diagram of the control system with tabular adjusting

Fig. 6 shows a diagram of the control system with PL adaptation of the parameters of the PI-controller. The PL adaptation unit based on the *N* load signal calculates the controller's settings for each change in the load *N*.

Fig. 7 shows a diagram of the control system with the adaptation of the parameters of the PI-controller based on fuzzy logic. This controller is similar to the one illustrated in Fig. 6, the used unit for adapting the parameters of the controller is a fuzzy logic unit.

Fig. 8 shows the comparison of the plots of transitional processes. The simulation was carried out in the Simulink programming environment using the MATLAB software package (USA).

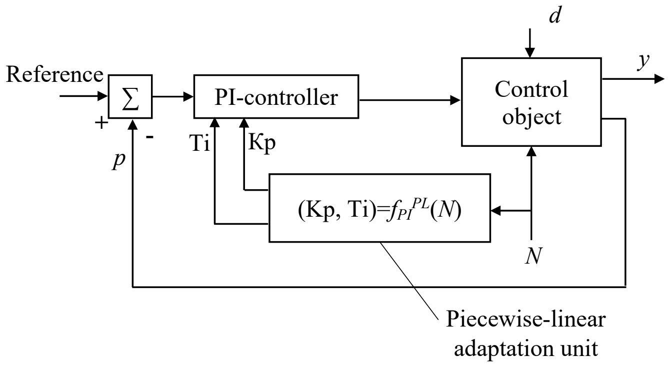


Fig. 6. Diagram of the control system with PL adaptation

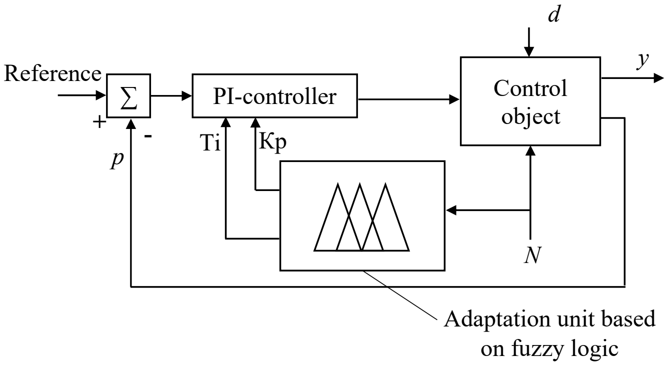
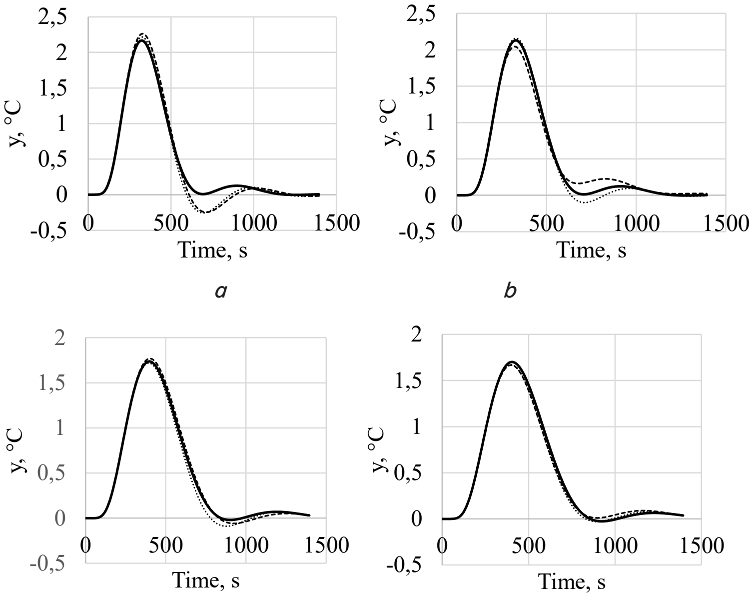


Fig. 7. Diagram of the control system with adaptation based on fuzzy logic



a *b*

c *d*

Fig. 8. Comparison of transitional processes: *a* – N=81 %; *b* – N=82 %; *c* – N=93 %; *d* – N=94 %; ····· – fuzzy, ---- – tabular, ——— – PL

The plots in Fig. 8 show the operation of control systems at the boundary of switching between tabular values. Data on the quality indicators of control systems at other load N values are summarized in Table 1.

5. 3. Comparative analysis of quality indicators of control systems with parametric adaptation of the PI-controller

The comparison of the operation of control systems over the entire range of loads of the power unit is summarized in Table 1. For comparison, the following quality indicators were selected: overshoot, setting time, undershoot, integral absolute error (IAE). In bold, the best indicators among the three systems are highlighted, in terms of each indicator and load.

Table 1

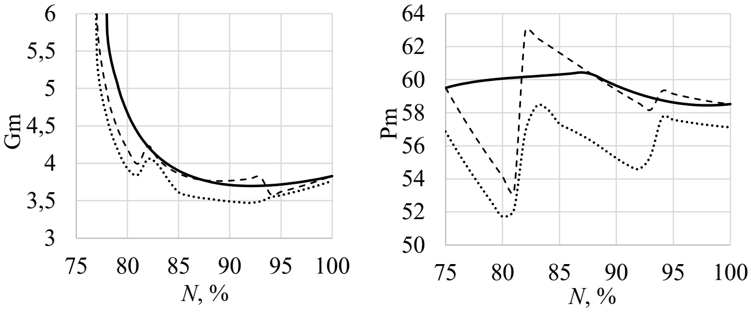
Indicators of the quality of functioning of systems with different methods of adaptation

Indicator	Adaptation method	Load N, %						
		75	81	82	87.5	93	94	100
Overshoot	Fuzzy	**2.36**	2.22	2.16	**1.88**	**1.72**	**1.67**	1.50
	Tabular	2.39	2.26	**2.04**	1.91	1.77	**1.67**	1.50
	PL	2.39	**2.17**	2.13	1.90	1.74	1.70	1.50
Setting time, s	Fuzzy	**950**	1110	1090	**1198**	1321	**1340**	1152
	Tabular	955	1130	1085	1212	**1292**	1345	**914**
	PL	955	**1060**	**1080**	1212	1321	**1340**	**914**
Undershoot, %	Fuzzy	5.0	11.5	4.6	3.4	5.2	1.8	4.8
	Tabular	**2.0**	10.9	–	–	3.3	–	**3.0**
	PL	**2.0**	–	–	–	**1.1**	1.5	**3.0**
IAE	Fuzzy	**654.3**	722.9	685.5	**653.7**	**663.3**	**655**	**680.2**
	Tabular	659.2	748.7	666.2	672.9	701.8	657.9	680.7
	PL	659.2	**664.3**	**665.2**	671.3	676.2	677.4	680.7

No optimal method of adaptation according to quality indicators can be detected. The system with fuzzy logic demonstrates better performance at loads greater than average. In particular, it is definitely better in overshoot and IAE. With loads from minimum to medium, the best indicators are demonstrated by the control system with PL adaptation. The system with tabular adjusting also in some cases has better or close to better performance. Indicators of the quality and the form of transient processes with loads of more than 90 % practically do not differ. This suggests that the control object enters the design mode of operation and the dynamic properties change less.

In addition to evaluating adaptation methods based on the specified quality indicators, it is advisable to assess the stability of these control systems. The study of the stability of systems with the adaptation of the parameters of the controller is complicated by the change in the parameters of both the controller and the control object. In the case of unsuitability of analytical procedures for such studies, an experimental approach may be a possible solution [15]. The main idea is the need for synthesis and further computer analysis of models of the control object and the controller. The use of modern computer technology and software modeling packages makes it possible to conduct a comprehensive analysis of complex multidimensional systems, regardless of the number of signals that affect them and the nature of changes in the parameters of models [20, 21].

Fig. 9 shows the dependences of changes in stability margin for gain Gm and phase Pm.



a *b*

Fig. 9. Comparing stability margin: *a* — for gain; *b* — for phase; ····· — fuzzy, ---- — tabular, ——— — PL

The plots in Fig. 9 were constructed by determining the stability margin Gm and Pm in the frequency domain. For each load *N* value in the range from 75 to 100 % in increments of 1 %, by using the software, the frequency characteristics of the disconnected control system were determined. Knowing in advance the changes in the settings of the controller and the control object depending on the load, it is possible to consider the control system with adaptation as linear for each pair of Kp and Ti settings.

6. Discussion of results of the functioning of control systems with parametric adaptation of the PI-controller

It is worth noting that there is no significant difference in quality indicators in all three schemes. Most transition processes differ at the boundary of switching between 81 and 82 % of the load. This is especially true of the overshooting indicator for circuits with tabular and fuzzy methods of adaption. When the load changes from 81 to 82 %, this indicator improves abruptly for both circuits. The difference in transient processes with loads of more than 90 % is eroded. The gain coefficients of the sections of a WSFP decrease with an increase in load. This factor also has a beneficial effect on the quality of control and the stability of the control system. It can be argued that the control object enters a saturation mode and its sensitivity to changes in the settings of the PI controller decreases. This is expected in view of Fig. 2. One clearly sees that after the average load *N* level, the angle of change in the Kp and Ti parameters decreases.

More clearly, the difference between schemes with different methods of adaptation is given by the analysis of stability margin when changing the load. In Fig. 9, *a*, the system with PL adaptation of parameters demonstrates the largest reserves of stability when changing the load. For the purpose of clarity, the scale of Gm in Fig. 9, *a* is bounded from above by a value of 6. At loads close to the minimum (75–76 %), the Gm margin for all three circuits is very large and equals 15–16. In the range from 87.5 to 93 %, in the scheme with tabular adjusting, there is an increase in the margin in terms of gain. This can be explained by a decrease in the gain coefficient of the control object at a constant value of the controller's proportional gain. The tabular adjustment scheme is characterized by jumping changes in the Gm margin at the time of change of setting at loads *N*=81–82 % and 93–94 %. The system with fuzzy adaptation throughout the range has the smallest margin in terms of gain. The jumping change in the Gm margin occurs at loads *N*=81–82 %; at *N*=93–94 %, such a jump does not occur. This fact is not obvious and could not be predicted on the basis of the static characteristics of the fuzzy adaptation unit (Fig. 4). Common to all three circuits is an avalanche-like reduction in the Gm stability margin while increasing the load from the minimum value. This is due to an increase in the time delay in the signal for temperature based on LRP. This parameter has the least inertia at minimal load. The increase in the transport delay or the time of the transfer function of this signal has a very negative effect on the stability margin of the entire system.

Fig. 9, *b* shows the nature of change in the margin for the Pm phase. A plot for the scheme with tabular adjustment has a sharp change in the values of margin for the Pm phase. The time constants of the object increase with increasing load; the hodograph turns towards the point (–1; *j*0). Accordingly, this affects the hodograph of the open system. Indicative is how the tabular change in the settings of the controller jumps sharply returns the margin for phase to acceptable values with a gradual increase in load. Similarly, the Pm margin changes in the system with fuzzy adaptation. Only the Pm margin values differ for these two schemes. For a system with fuzzy adaptation, the Pm margin values across the entire range are smaller than tabular adjustments. A completely different is the system with PL adaptation. With an increase in load in the range from 75 to 87.5 %, the Pm margin increases. At *N*=87.5 %, in the scheme with PL adaptation, the Pm margin reaches its maximum. With a further increase in load, the Pm margin decreases. The range of change in the Pm margin in the scheme with PL adaptation when changing the load is the smallest. That is, the Pm margin practically does not change on the entire range of load changes. Taking into consideration the analysis of the stability of the schemes under consideration, it can be concluded unequivocally that the scheme with PL adaptation of the parameters of the PI-controller is the best.

The current study was conducted for the model of the control system of the WSFP of the direct-flow pulverized coal power unit at TPP with a capacity of 300 MW. The proposed approach could be applied for other types of power boilers, including those that use other fuels. It is only worth noting that this would require additional research to clarify the models of the relevant objects.

A possible direction of further research is the use of schemes and algorithms described in [13, 15]. However, this will require, first of all, addressing the issue of filtering measurable technological parameters that are planned to be used for adaptation.

The clear results were demonstrated by the methodology for assessing the stability of adaptive systems when analyzing and comparing various adaptation methods. An interesting direction is the application of a given approach to the synthesis of adaptive systems, which is promising for further research.

7. Conclusions

1. The functional dependences of the units of adaptation of parameters of the PI-controller according to the tabular, piecewise-linear methods, and the method of adaptation based on fuzzy logic have been determined. The main signal by which the adaptation is carried out is the signal for the current load of the power unit. Static characteristics of the controller settings depending on the load of the power unit have been defined. From the point of view of setting up the adaptation unit, the simplest method of adaptation is tabular. Most of the time to configure the adaptation unit should be spent in the case of fuzzy logic.

2. We have designed schemes of control systems with the adaptation of parameters of the PI-controller. For the tabular adaptation method, it is convenient to use three separately configured PI controllers with a switching unit. For piecewise-linear and fuzzy adaptation methods, it is necessary to implement a more complex scheme in which the parameters of the controller are recalculated each time the load changes.

3. Our comparative analysis of various methods of adaptation has revealed that the simplest method of tabular adjustment is inferior to the piecewise-linear method of adaptation. This assessment is made on the basis of the analysis of direct, integral, and frequency indicators of the quality of functioning of control systems. It was shown that when working under a reduced load, using the piecewise-linear method of adaptation makes it possible to significantly reduce the integral absolute quality assessment (to 11 %) and, as a result, reduce energy consumption in transition modes. More informative, in comparison with direct quality indicators, was the proposed method of assessing the stability of systems with the adaptation of parameters. With its help, the advantage of the piecewise-linear method of adaptation was clearly demonstrated. The best result in terms of increasing the stability margin compared to other methods (up to 15 %) is produced by a system with a piecewise-linear method of adaptation in the load range from 75 to 81 %.

References

1. Eser, P., Chokani, N., Abhari, R. S. (2017). Operational and financial performance of fossil fuel power plants within a high renewable energy mix. Journal of the Global Power and Propulsion Society, 1, 2BIOTO. doi: https://doi.org/10.22261/2bioto
2. Zvit z otsinky vidpovidnosti (dostatnosti) heneruiuchykh potuzhnostei dlia pokryttia prohnozovanoho popytu na elektrychnu enerhiyu ta zabezpechennia neobkhidnoho rezervu u 2021 rotsi. Available at: https://ua.energy/wp-content/uploads/2021/11/ERAA-UA-2021-v6.pdf
3. Gonzalez-Salazar, M. A., Kirsten, T., Prchlik, L. (2018). Review of the operational flexibility and emissions of gas- and coal-fired power plants in a future with growing renewables. Renewable and Sustainable Energy Reviews, 82, 1497–1513. doi: https://doi.org/10.1016/j.rser.2017.05.278
4. Rúa, J., Verheyleweghen, A., Jäschke, J., Nord, L. O. (2021). Optimal scheduling of flexible thermal power plants with lifetime enhancement under uncertainty. Applied Thermal Engineering, 191, 116794. doi: https://doi.org/10.1016/j.applthermaleng.2021.116794
5. Zielińska-Sitkiewicz, M., Chrzanowska, M., Furmańczyk, K., Paczutkowski, K. (2021). Analysis of Electricity Consumption in Poland Using Prediction Models and Neural Networks. Energies, 14 (20), 6619. doi: https://doi.org/10.3390/en14206619
6. Sviridenko, V. P., Poputnikov, A. B. (2001). Opyt modernizatsii skhemy regulyatora teplovoy nagruzki kotla TPP-210A pri rabote na ugol'noy pyli. Energetika i elektrofikatsiya, 4, 20–23.
7. Stepanets, A., Motoryna, D. (2014). Adaptive automatic control system with PI-controller frequency tuning. Eastern-European Journal of Enterprise Technologies, 2 (9 (68)), 45–48. doi: https://doi.org/10.15587/1729-4061.2014.23340
8. Fahmy, R. A., Badr, R. I., Rahman, F. A. (2014). Adaptive PID Controller Using RLS for SISO Stable and Unstable Systems. Advances in Power Electronics, 2014, 1–5. doi: https://doi.org/10.1155/2014/507142
9. Kovrigo, Y. M., Konovalov, M. A., Bunke, A. S. (2012). Modernizing the heat load control system of a once-through boiler unit at a thermal power station using a dynamic corrector. Thermal Engineering, 59 (10), 772–778. doi: https://doi.org/10.1134/s0040601512100072
10. Bahan, T. (2017). Synthesis of robust controller with an internal model for objects without self-alignment. Eastern-European Journal of Enterprise Technologies, 4 (2 (88)), 27–33. doi: https://doi.org/10.15587/1729-4061.2017.108531
11. Shteynberg, Sh. E., Serezhin, L. P., Zalutskiy, I. E., Varlamov, I. G. (2004). Problemy sozdaniya i ekspluatatsii effektivnykh sistem regulirovaniya. Promyshlennye ASU i kontrollery, 7, 1–7.
12. Qin, Y., Sun, L., Hua, Q., Liu, P. (2018). A Fuzzy Adaptive PID Controller Design for Fuel Cell Power Plant. Sustainability, 10 (7), 2438. doi: https://doi.org/10.3390/su10072438
13. Shtifzon, O., Novikov, P., Bahan, T. (2018). Development of adaptive fuzzy-logic device for control under conditions of parametric non-stationarity. Eastern-European Journal of Enterprise Technologies, 1 (2 (91)), 30–37. doi: https://doi.org/10.15587/1729-4061.2018.121749
14. Kermani, A., Kargar, S. M. (2021). Fuzzy modelling of combustion efficiency and control of excess air flow case study: 320-MW steam unit/Isfahan Power Plant/Iran. Clean Energy, 5 (2), 229–242. doi: https://doi.org/10.1093/ce/zkab005

15. Novikov, P. V., Shtifzon, O. Y. (2020). Stability analysis of control system based on two-channel fuzzy controller. Automation of Technological and Business Processes, 12 (1), 25–32. doi: https://doi.org/10.15673/atbp.v12i1.1700
16. Stepanets, O., Mariiash, Y. (2018). Analysis of influence of technical features of a pid¬controller implementation on the dynamics of automated control system. Eastern-European Journal of Enterprise Technologies, 3 (2 (93)), 60–69. doi: https://doi.org/10.15587/1729-4061.2018.132229
17. Sarda, P., Hedrick, E., Reynolds, K., Bhattacharyya, D., Zitney, S. E., Omell, B. (2018). Development of a Dynamic Model and Control System for Load-Following Studies of Supercritical Pulverized Coal Power Plants. Processes, 6 (11), 226. doi: https://doi.org/10.3390/pr6110226
18. Novikov, P. V., Bunke, A. S. (2020). Modeling of control system of temperature mode of direct-flow steam boiler based on two-channel fuzzy controller. Scientific Notes of Taurida National V.I. Vernadsky University. Series: Technical Sciences, 31 (2 (70)), 132–139. doi: https://doi.org/10.32838/2663-5941/2020.2-1/21
19. Novikov P. V. (2019). Avtomatyzatsiya protsesiv keruvannia inertsiynymy kanalamy enerhobloku teplovoi elektrostantsiyi z vykorystanniam dvokanalnoho nechitkoho kontrolera. Kyiv, 191. Available at: https://ela.kpi.ua/bitstream/123456789/29399/1/Novikov_diss.pdf
20. Voloşencu, C. (2021). Stability Analysis of Systems with Fuzzy PI Controllers Applied to Electric Drives. Mathematics, 9 (11), 1246. doi: https://doi.org/10.3390/math9111246
21. Chao, C.-T., Chen, D.-H., Chiou, J.-S. (2021). Stability Analysis and Robust Stabilization of Uncertain Fuzzy Time-Delay Systems. Mathematics, 9 (19), 2441. doi: https://doi.org/10.3390/math9192441