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ANALYSIS OF INFLUENCE OF TECHNICAL FEATURES OF A PID-CONTROLLER IMPLEMENTATION ON THE DYNAMICS OF AUTOMATED CONTROL SYSTEM

В умовах інтенсифікації, максимізації рентабельності та забезпечення технологічної безпеки виробництва виникає проблема регулювання, оптимізації, вдосконалення структури систем автоматичного управління. Незважаючи на довгу історію розвитку та наявність великої кількості патентів, розробок, публікацій, на сьогоднішній день залишається багато актуальних проблем, пов'язаних з практичною реалізацією ПІД-регулятора: уніфікація структури ПІД-регулятора, реалізація диференціальної складової, інтегральне насичення та безударна передача параметрів і режимів роботи.

У статті досліджується вплив нелінійностей, шуму, перешкод, функцій та особливостей ПІД-регулятора на динаміку системи автоматичного керування. Показано, що для максимальної ефективності реалізації ПІД-регулятора для керування інерційними об'єктами з транспортним запізнюванням потрібно застосовувати комплексний підхід: обмеження швидкості зростання збурення по завданню та умовного інтегрування для усунення інтегрального насичення; одночасне застосування експоненціального фільтра виміряної величини та диференціатора з фільтром високих частот для мінімізації впливу шумів та завад на перехідні процеси; відслідковування поточного стану системи дозволяє запобігти "удару" при зміні режимів роботи ПІД-регулятора; введення зони нечутливості регулятора потенційно забезпечить триваліший період експлуатації виконавчого механізму.

Здійснено математичне моделювання системи автоматичного регулювання розрідження у топці котлоагрегату з врахуванням запропонованого комплексу рішень. Наведені рекомендації дозволяють реалізувати ПІД-регулятор, придатний для практичного застосування з врахуванням стохастичності, нелінійності, квазістаціонарності та обмежень технологічних процесів.

Комплексна оцінка та врахування даних проблем сприятимуть підвищенню ефективності та надійності роботи обладнання, зменшенню споживання енергії та часу досягнення заданої цілі в процесі автоматичного регулювання, без зміни структури системи управління

Ключові слова: ПІД-регулятор, інтегральне насичення, фільтрація шумів, диференціатор, безударна передача

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1. Introduction

Under conditions of intensification, maximization of profitability and ensuring technological safety of production, certain problems emerge related to the adjustment, optimization and improvement of the structure of automated control systems. Despite the emergence and gaining popularity of advanced control methods, such as Model Predictive Control, Fuzzy Logic, controllers based on the proportional-integral-differential (PID) law of regulation are the most popular at present, with a share of up to 90 % [1].

The operation and adjustment of regulation system is the major problem today. Thirty percent of the controllers used in industry are incorrectly adjusted [2] because natural nonlinearities of technical implementation have not been taken into consideration. In many PID controllers, differential component is shut down. The main causes of shutdown include complexity of adjustment and insufficient knowledge of the dynamics of control process. The result obtained is the incorrect adjustment of parameters leading to worsening efficiency of a technological process control and performance of a unit in general.

Assessment and consideration of similar problems can improve efficiency of equipment operation, reduce energy consumption, and shorten time spent to achieve the set target in the process of automatic control without changing the system structure. That is why practical realization of the PID controller with consideration of stochasticity, nonlinearity, and quasi-stationarity of technological processes in conditions of limitation is an important problem today.

2. Literature review and problem statement

Despite the long history of development and existence of a large number of patents, solutions and publications [2–4], many problems associated with the practical implementation of the PID controllers remain unsolved. The main problems include unification of the PID controller structure, implementation of a differential component [4], integral saturation and nonimpact transmission of parameters and modes of regulation that does not lead to a jump-like change of the control action [5].

PID controllers as the most widespread type of automatic controllers are produced in many variants [6] and there is much research addressing their properties [5, 7]. As a rule, they relate to individual issues and are considered in an academic idealized environment. This is true for a number of conditions, such as the linearity of the control object, a slight deviation of the technological variable from the work point, ideal actuator, etc.

There is a variety of PID controller structures [8]. This diversity is associated with complexity of practical implementation and the developers' attempt to hide the structure and principles of their controllers. There are three most common forms of writing the PID law of regulation [9].

A sequential [1] or classical algorithm (1) is the oldest common implementation that has been used since the time of the first pneumatic and electric hardware controllers born by technical capabilities of hardware forming the components of the regulation law.

$$W_C(s) = K_P\left(1+\frac{1}{T_i s}\right)(1+T_d s), \tag{1}$$

where $W_c(s)$ is the transfer function of the regulation law in the Laplace space, s is the complex variable of the Laplace transform, K_p is the gain factor, T_i is the time of integration, T_d is the time of differentiation.

Despite the apparent obviousness of the structure, the parallel form of writing of the PID law of regulation (2) is not recommended for use by some researchers [10] because of presence of the controller gain factor which is divided into three constituents:

$$W_C(s) = K_P + \frac{1}{T_i s} + T_d s. \tag{2}$$

The International Society of Automation which is an international leader in development of automation standards recommends [4] using form (3) as a standard of the PID controller structure with a clearly expressed gain factor:

$$W_C(s) = K_P\left(1+\frac{1}{T_i s}+T_d s\right). \tag{3}$$

Different forms of the regulation law can be reduced to each other by means of mathematical dependences and a number of assumptions that enable conversion of the coefficient values. In certain cases, proportional, integral and differential components may be absent creating individual cases of the PID regulation law: P-, PI-, PD-, I-controller.

Very often, practical application of controllers is limited to a statement of the facts [11–13] of availability of several options or methods for implementation of practical functions. Emphasis is made on a specific solution without comparing it with existing ones.

In implementation of the PID controllers, filters are not always used or they are set up incorrectly. The differential component of the controller amplifies high-frequency interferences, short-term disturbances, and noise. These problems are aggravated by the fact that dynamics of processes is unknown a priori, there is a mutual influence of different systems of automatic control. Filtering of noise and influence of the differential component of the controller are the subject of interest of many researchers [14, 15] proposing their own approaches to and criteria of solving this problem but there is no an unambiguous recommendation so far. Filtering of information signals can improve reliability of information but because of the above factors, it is not always possible and results in an additional system lag [16].

In the regulation process, it is practically always necessary to take into consideration nonlinearities of a "limitation" type. This nonlinearity is associated with natural limitations on power, speed, rotational speed, valve opening, etc. The most common manifestation of the limitation mode is the so-called "integral saturation". Methods for eliminating integral saturation are the subject of discussions, publications, inventions, and commercial secrets of many companies developing software for controllers [5]. To date, there is no single procedure that would completely solve the problem of integral saturation [4, 5]. Paper [17] considers ways of taking into account limitations of a "saturation" type in control systems but no final recommendation for their use is given. Sometimes, depending on the requirements to the object's behavior, this approach may even develop into complicated structures [18] with their own limitation controllers. These are unique cases unsuitable for mass application.

Situations that change the mode of equipment operation, the system structure and production needs arise in automatic control of technological processes. This leads to the necessity of tracing operating modes and nonimpact switching [4, 5]. Recommendations of various authors complicate selection of an appropriate configuration for a practical use.

For digital implementation of the PID controllers which is prevalent in the era of computer technologies, a correct choice of the sampling period for calculating the algorithm is also important. Paper [19] reports results of a study on the influence of this factor on behavior of the control system and shows differences in the values of settings. At the same time, because of the high speed of implementation of current programs, this factor exerts influence on the choice of numerical methods of implementing integration and differentiation more than on dynamics of the control object.

Numerous researchers are also searching for modernization of PID controllers and providing additional properties. In study [20], introduction of correction of a control signal at the initial stage of the transient process improves the control quality but simultaneously complicates the controller structure. Practitioners do not perceive enthusiastically new approaches to control as they require new competencies and are not easy for intuitive perception which complicates

making prompt decisions during start-ups. A relatively new approach using an internal model of the object directly in the controller structure [21] which becomes widespread due to availability of implementation of the model of a specified complexity based on modern PLCs cannot serve as a substitute for the PID controllers. If there is a significant transportation lag, processing of disturbances may be ineffective and requiring even more complication of the controller structure [22]. That is, it requires an individual approach to each object because of necessity of a precise definition of the model while the PID summarizes dynamics of the object class by means of the adjustment parameters. The PID controller can be adjusted for a large number of model types [6].

The mathematical PID controller is a theoretical "ideal" of a real controller. For its practical implementation, it is necessary to consider the features brought about by actual conditions of the technological process. The final range of changes of physical parameters in the system is limited to the accuracy of measurements and the presence of noise, variable loads, continuity of the technological processes, mutual influence of the controller processes, presence of virtually all systems of nonlinearities such as saturation, speed limitation, hysteresis and backlash, necessity of smooth (nonimpact) switching of regulation modes, etc. influences the practical implementation of the PID controllers.

3. The aim and objectives of the study

This study objective was to evaluate the combined effect of nonlinearities and functions of the PID controller connected with its practical realization based on the present-day hardware means on dynamics of the transient processes taking place in the control object. The study of causes and consequences of introduction of nonlinearities of various natures should enable an effective control of objects taking into consideration behavior of controllers in various operation modes.

To achieve the objective, the following tasks were formulated:

– to study influence of the measured signal filtering and implementation of the differential component of the controller on the transient process in a closed system;

– to evaluate methods of eliminating saturation of the integral component in the structure of the PID controller and the effect on dynamics of a single-loop control system;

– to consider contribution of nonlinearity of a "speed limitation" type of the controller setpoint to the change of dynamics of the transient process which is important for exclusion of the intense influence on the actuator and operation of the controller in a cascade control structure;

– to consider implementation of nonimpact switching of parameters and operating modes of the PID controller from the point of view of influence on the actuator and the transient processes in the system.

4. Structure of the studied system of automatic control and the methods of mathematical modeling

4. 1. The system under study and the control object

The most widespread principle of construction of automatic control systems to date is the principle of deviation control (Fig. 1) based on the proportional-integral-differential (PID) law of regulation [1].
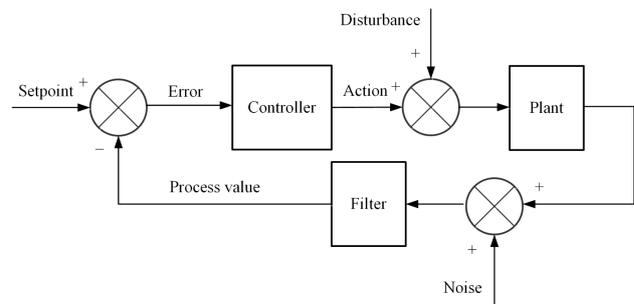
Fig. 1. Block diagram of the automatic control system with feedback in the presence of external perturbations and noise

Boiler units are the typical objects for automatic control systems in the heat power engineering. The rarefaction control loop in the boiler furnace was taken for the study of practical implementation of the PID controller. The obtained study results can be extrapolated to the objects with similar dynamics. Presence of a slight rarefaction in the boiler upper furnace is necessary to ensure flame stability in the combustion zone and removal of flue gases from the boiler. The problems of regulating rarefaction in the boiler furnace include presence of high-frequency noises in measurements, external perturbation (change of the air flow) and internal perturbation (violation of the gas-air conditions). The control object in the channel "the smoke pump rotation speed – rarefaction in the boiler furnace" has a transfer function (4) [23]:

$$W_p(s) = \frac{0,55}{5s+1} e^{-2s}. \qquad (4)$$

As a model of high-frequency noise, the band-limited white noise model in Matlab Simulink environment was used with the following parameters. Noise power: 0.1, sample time: 0.2, speed: 334. The obtained variance of high-frequency noise when measuring rarefaction in the boiler furnace was 0.4664.

4. 2. Initial settings and the procedure for assessing quality of functioning of the automatic control system

The standard structure of the PID controller was taken for the studies in accordance with the recommendations of the ISA [4]. The controller parameters (5) were calculated using the express method – Modified minimum ITAE - Smith [6]:

$$K_p = \frac{0,965}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0,855} = \frac{0,965}{0,55}\left(\frac{5}{0,2}\right)^{0,855} = 3,84\left[\frac{\%}{Pa}\right],$$

$$T_i = 1,26 \cdot T_m = 1,26 \cdot 5 = 6,3[s];$$

$$T_d = 0,308 \cdot \tau_m = 0,308 \cdot 2 = 0,616[s]. \qquad (5)$$

Quality of regulation in the process of practical implementation of the PID controller was estimated by means of indicator (6), the Integral of the Time-weighed Absolute Error (ITAE):

$$ITAE = \int_0^{t_p} t \cdot |e(t)| dt. \qquad (6)$$

Quality of the regulation process when using ITAE is determined by time-weighed imbalance. In this indicator,

the effect of the start of the regulation process (when deviation from the setpoint is quite large) is minimized and more attention is paid to the imbalance that persists over time. Therefore, the ITAE is an indicative criterion used in many methods of controller setting because it characterizes quality of transient processes [6, 7].

The simulation procedure was performed in the Matlab Simulink environment. An algorithm for solving equations ode23s (stiff/mod. Rosenbrock) with a variable step was chosen. Absolute and relative accuracy of the calculations was 0.001.

5. Results obtained in the study of implementation aspects of the practical PID controller functions

5. 1. Differential component of the controller and the effect of noise on dynamics of the automated control system

The transient processes of the system of automatic regulation of rarefaction in a boiler furnace for an "ideal" PID controller are shown in Fig. 2.
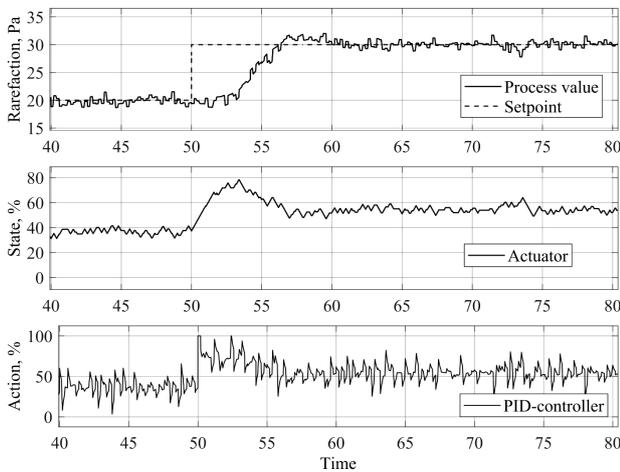
Fig. 2. Transient processes of the system of automatic rarefaction (Pa) regulation in the boiler furnace using an "ideal" PID controller

ITAE of the transient process of the system of automatic regulation of rarefaction in the boiler furnace with a mathematical PID controller was 5533. The result obtained was the control result for this study.

Noises amplified by a differentiator lying outside the operating frequencies of the PID controller can be reduced by means of a low-cut filter [2, 4, 5] (Fig. 3).

As a result of application of the differentiator with the low-cut filter, ITAE of the transient process of regulation of rarefaction in the boiler furnace was 5432.

Another approach to mitigating the effects of short-term perturbations and noise is the use of a filter included in the regulation system in series with the controller. To study practical implementation of the PID controller, an exponential filter [4] (Fig. 4) was used; ITAE of the transient process was 5424.

Simultaneous use of the exponential filter of the measured value and the differentiator with a low-cut filter (Fig. 5) has made it possible to obtain ITAE of the transient process of regulation of rarefaction in the boiler furnace equal to 5376.
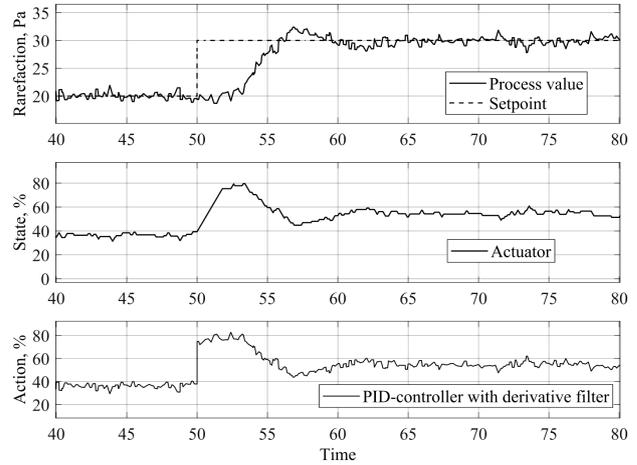
Fig. 3. Transient processes of the system of automatic regulation of rarefaction (Pa) in the boiler furnace with the use of a differentiator with a low-cut filter
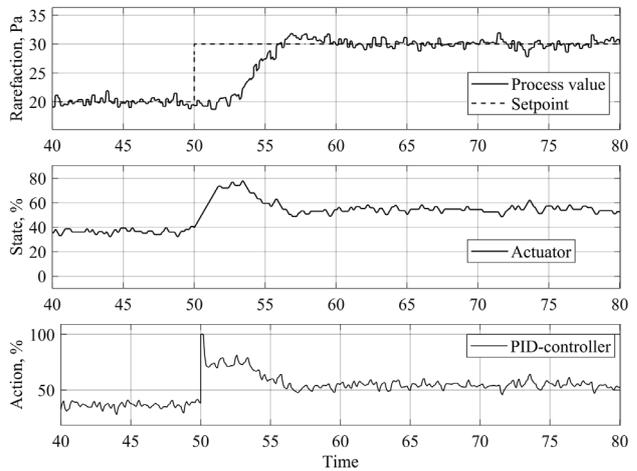
Fig. 4. Transient processes of the system of automatic regulation of rarefaction (Pa) in the boiler furnace with the use of an exponential filter
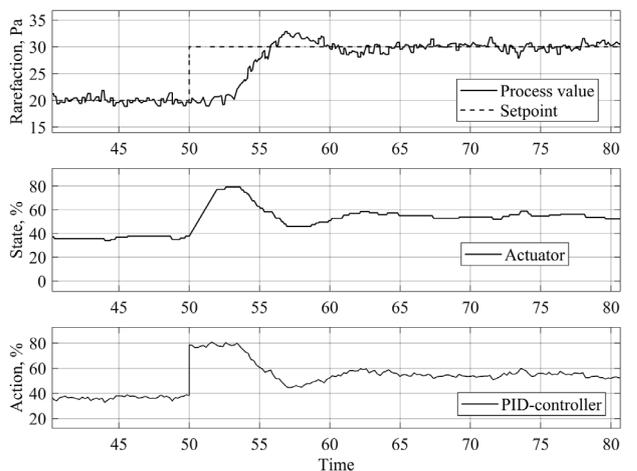
Fig. 5. Transient processes of the system of automatic regulation of rarefaction (Pa) in the boiler furnace using an exponential filter of the measured value and a differentiator with a low-cut filter

Fig. 6 shows transient processes of the automatic regulation of rarefaction in the boiler furnace with an

additional introduction of the zone of insensitivity of the controller [4, 7].
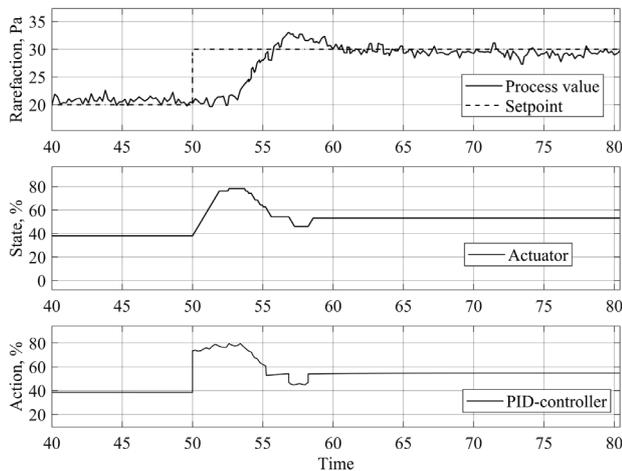
Fig. 6. Transient processes of the system of automatic regulation of rarefaction (Pa) in the boiler furnace with an additional introduction of insensitivity zone of the controller

The experiment shows that introduction of the zone of insensitivity favorably affects movement of the actuator which can extend its operation life. This non-linearity of determination of the imbalance signal expressed in equating to the zero of the regulation error at its modulus value lower than the set threshold value makes it possible to reduce the number of the drive actuations if the technological variable is in the vicinity of the setpoint.

5. 2. Results obtained in the study of techniques for elimination of integral saturation of the PID controller

The transient process of the system of automatic regulation of rarefaction in the boiler furnace without elimination of integral saturation (Fig. 7) has provided ITAE of 8946. The result obtained is the control result for this study.
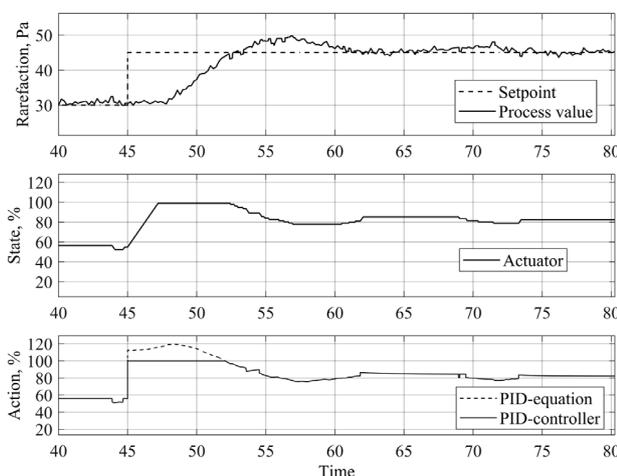
Fig. 7. Transient processes of the system of automatic regulation of rarefaction (Pa) in the boiler furnace without elimination of the integral saturation

The Control Loop Foundation [4] recommends to reduce the rate of growth of the setpoint signal, namely, to provide a linear (integral) transition to a new set value for a prede-

termined time, recommended 1–2 s (Fig. 8). ITAE of the transient process of regulation was 8361.
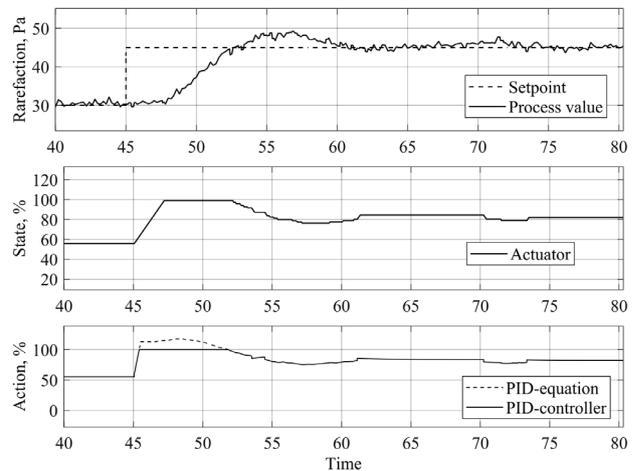
Fig. 8. Transient processes of the system of automatic regulation of rarefaction (Pa) in the boiler furnace with a linear limitation of the rate of the setpoint change

In the course of the study, it was decided to replace the linear (integral) limitation of the setpoint change rate (Fig. 8) in favor of passing the target signal through the aperiodic link of the first order (Fig. 9). As a result, ITAE of the process was 8171.
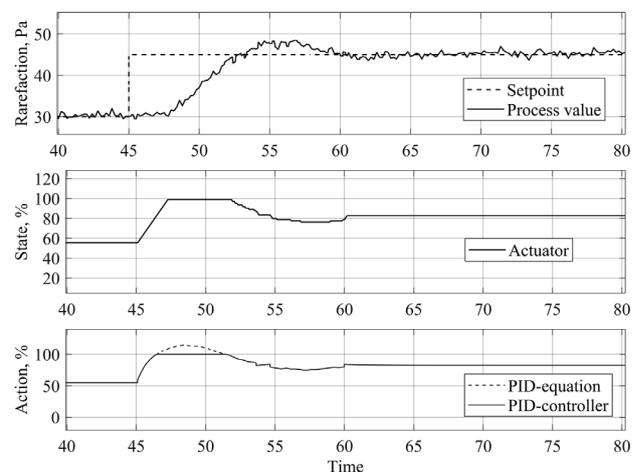
Fig. 9. Transient processes of the system of automatic regulation of rarefaction (Pa) in the boiler furnace with an aperiodic limitation of the rate of change of the setpoint

One of the methods for elimination of integral saturation consists in that the controller monitors magnitude of the regulation action on the object and once it reaches saturation, prohibition of integration (7) for the integral component of the controller is introduced (Fig. 10) [2, 5, 11]. ITAE of the transient controller process was 8177.

Having the actuator model (Fig. 11), it is possible to trace its output signal and compensate for the saturation effect by changing the signal applied to the integral component of the PID controller [5] (Fig. 12).

The signal u at the output of the actuator is measured (if possible) or calculated by means of the model. As a result, a disbalance signal is obtained (7):

$$e_s = u - v, \qquad\qquad\qquad (7)$$

where e_s is the signal of imbalance between the output of the controller and the output of the actuator, u is the output of the controller, v is the output of the actuator.
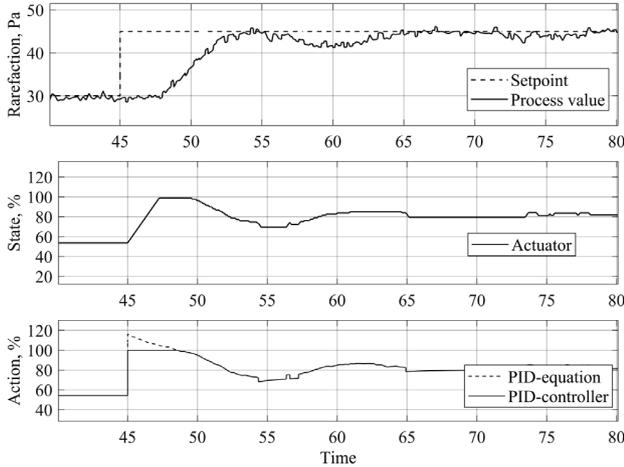
Fig. 10. Transient processes of the system of automatic regulation of rarefaction (Pa) in the boiler furnace with prohibition of integration
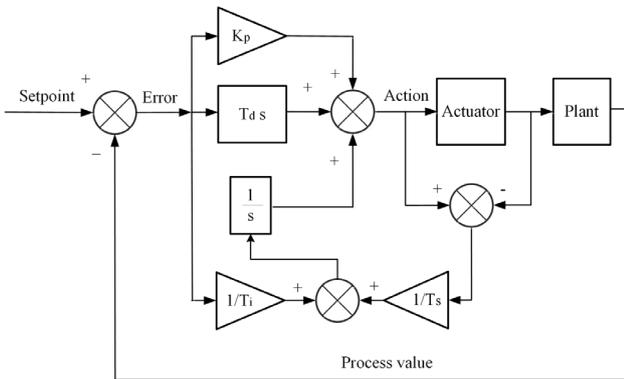
Fig. 11. Block diagram of saturation compensation using the model of the executive mechanism: u is the regulating action on the actuator; v is the output from the actuator; e_s is the signal of the imbalance between the output of the controller and the output of the actuator; K_p is the gain factor of the controller; T_i is the constant of the time of the controller integration; T_d is the constant of the time of the controller differentiation; T_s is the constant of time of compensation of the integral controller component; s is the Laplace transform

Consider possible values (7):

1) e_s=0: there is no compensation equivalent to the usual IP controller;

2) e_s<0: the executive mechanism enters the state of saturation. That is, an additional signal is subtracted from the imbalance signal at the input of the integral controller component which results in a slower rate of integration.

The time constant T_s determines dynamics of compensation of the error signal at the input to the integral component of the controller.

ITAE of the transient process of regulating rarefaction in the boiler furnace with compensation of saturation using the actuator model at T_s=3 s was 8115.
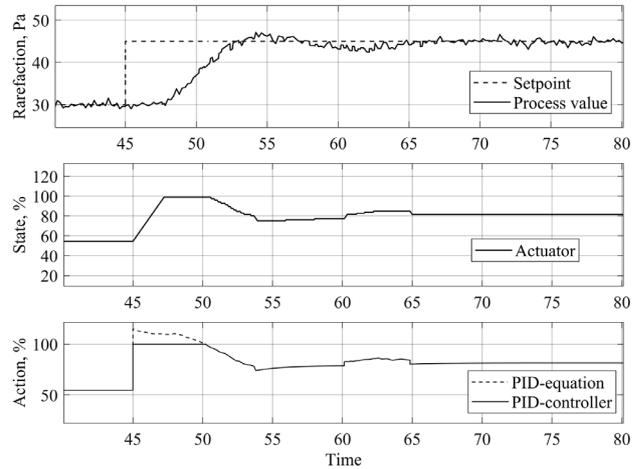
Fig. 12. Transient processes of the system of automatic regulation of rarefaction (Pa) in the boiler furnace with compensation of saturation by means of the actuator model at T_s=3 s

In order to achieve high qualitative indicators of elimination of integral saturation during practical implementation of the PID controller, a decision was made to apply an integrated approach, namely, simultaneous implementation of limitation of the rate of target perturbation growth and conditional integration [5] (Fig. 13).
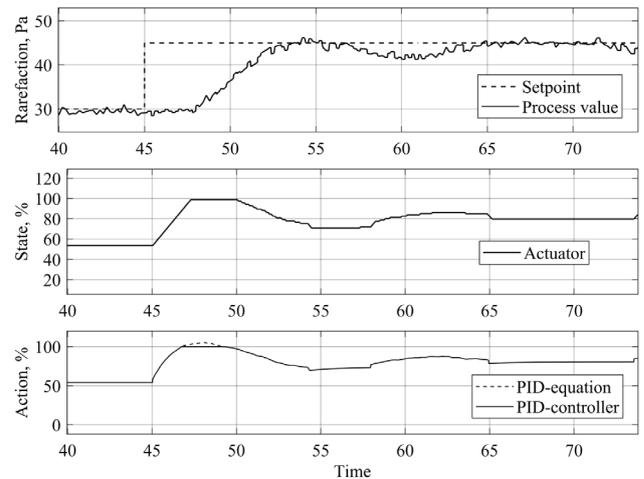
Fig. 13. Transient processes of the system of automatic regulation of rarefaction (Pa) in the boiler furnace with a simultaneous implementation of limitation of the rate of target growth of disturbance and conditional integration

ITAE of the transition process of regulation with a simultaneous implementation of limitation of the rate of target disturbance growth and conditional integration was 7955.

5. 3. Providing nonimpact switching of parameters and modes of the automatic regulation system

Fig. 14 shows the transient process of automatic regulation of rarefaction in the top of the boiler furnace with and without consideration of the problems of nonimpact switching. Features of the process control always require changes of operating modes from automatic to manual and vice versa, e. g. to diagnosticate equipment, switch a unit to a nominal operation mode, eliminate emergency situations, etc.
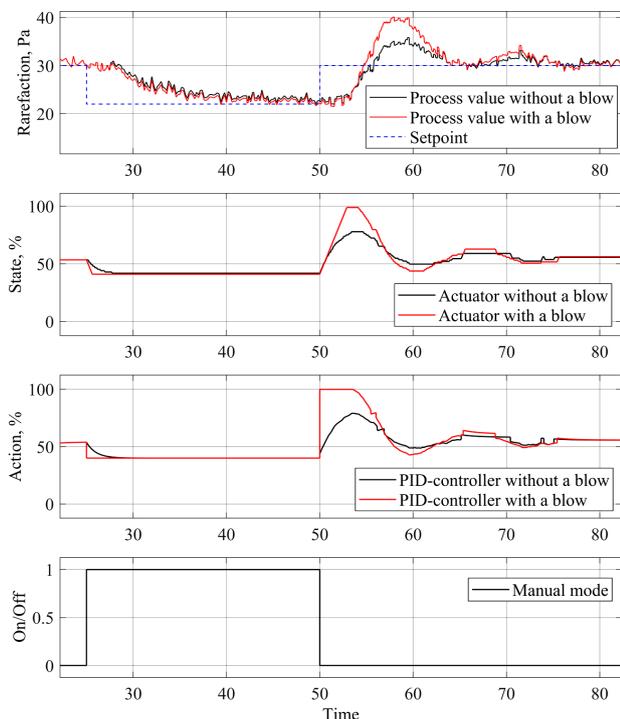
Fig. 14. Transient processes of the automatic system of regulation of rarefaction (Pa) in the boiler furnace

In the period from 25 to 50 seconds of the given transient process, the controller has been manually switched to the manual mode (the controller output: 40 %). ITAE of the transient process without taking into 13480. ITAE was 11090 when taking into consideration the problem of nonimpact mode switching.

6. Discussion of results of mathematical modeling of a practically suitable PID controller

An important problem of numerical differentiation consists in the usual situation of calculating the derivative as a difference between two close (by the magnitude) values of the function, so there is always an error in calculations. Also, the differentiator amplifies high-frequency interferences, short-term disturbances and noise [2]. High-frequency noise is harmful because it causes wear and failure of boiler fittings and electric motors. Reliability of operation of fittings and electric motors determines quality of operation of the system in general. Therefore, signal filtration and minimization of the high-frequency noise effect are primarily aimed at reducing wear of actuators. In the general case, if a $A\sin(\omega t)$, signal is applied to the differentiator input, a $A\cos(\omega t)$ signal is obtained at the actuator output, that is, amplitude of the signal at the differentiator output increases with an increase in frequency. In other words, the differential component of the controller amplifies high-frequency interferences, short disturbances and noise. Interferences amplified by the differentiator that are outside the operating frequencies of the PID controller but not filtered by the controller hardware can be weakened by means of the low-cut filter (Fig. 3) [2, 4, 5] with a transfer function (8):

$$\frac{T_d s}{\alpha T_d s + 1},$$ (8)

where T_d is the constant of the differentiation time; α is the coefficient that sets the limiting frequency of the filter and is usually chosen from the range of 0.05...0.5 [5].

As a result of application of the differentiator with a low-cut filter, ITAE of the transient process of regulation of rarefaction in the boiler unit furnace was decreased by

$$100\,\% \cdot \left(1 - \frac{5432}{5533}\right) \approx 1{,}82\,\%$$

in comparison with the "ideal" PID controller. That is, the mathematical modeling showed a possible positive tendency of influence of additional components of the PID controller on dynamics of the real object.

Another approach to mitigating the effects of short-term perturbations and noise is the use of a filter included in the control system in series with the controller [4]. The following requirements are laid down to the filtered variable:

1) the estimate of variance of the filtering error should be minimal;

2) the mathematical expectation of the filtered signal should coincide with the mathematical expectation of the useful signal.

Noise is a stationary random process, additive with a useful signal. It has a zero mathematical expectation and an autocorrelation function (9):

$$R_e(\Delta\tau) = kD_y e^{-\alpha_y m\Delta\tau},$$ (9)

where $R_e(\Delta\tau)$ is the autocorrelation function of noise; D_y is the variance of the measured signal; k, m, α_y are the coefficients characterizing noise, at $k<1$ (the noise amplitude is less than the useful signal amplitude), $m>1$ (the noise has a higher frequency than the useful signal). This means that filtering is only possible when the variance of noise is less than the variance of the useful signal ($k<1$) and the noise frequency is higher than the useful signal frequency ($m>1$).

An exponential filter was used for a practical implementation of the PID controller (Fig. 4). Advantages of the exponential filter include simple software implementation, availability of one setup parameter and high accuracy of filtering. ITAE of the transient process of regulation of rarefaction in the boiler furnace with an exponential filter has decreased by

$$100\,\% \cdot \left(1 - \frac{5424}{5533}\right) \approx 1{,}97\,\%$$

in comparison with the "ideal" PID controller.

The conducted studies have shown expediency of using an integrated approach, namely, the simultaneous implementation of the differentiator with a low-cut filter and filtering of the measured signal (Fig. 5) in presence of stochastic noise and disturbances in the system. The applied approach has made it possible to improve stability of the system and quality of regulation compared with individual application of the above methods. This method has enabled reduction of ITAE of the transient process of regulating rarefaction in the boiler furnace by

$$100\,\% \cdot \left(1 - \frac{5376}{5533}\right) \approx 2{,}8\,\%$$

in comparison with the "ideal" PID controller.

It should be understood that the application of the described solutions introduces additional inertia in the regulation system which leads to a longer time of regulation. Therefore, for automatic control systems where regulation time is critical, it is not recommended to apply these methods.

The essence of the problem of integral saturation is as follows. If the signal at the input of the control object has entered the zone of saturation (limitation) and the signal of imbalance is not equal to zero, the integrator continues integration. Accordingly, the signal at its output increases but does not participate in the regulation process and does not affect the object due to the effect of saturation. A similar situation leads to an increase in duration of the transient process at the expense of the time taken to return the integral component from the saturation zone. The control system in this case becomes equivalent to the open system. For example, for the loop of temperature regulation in the furnace, the lower range "limitation" means absence of heating. However, there may be a situation where according to the PID law of regulation, it is necessary to subject the object to such a control action that corresponds to "negative heating", that is, cooling, to provide the desired regulation quality.

During the study of this problem, several known methods for minimizing and eliminating the effects of integral saturation were analyzed:

1. Restriction of the target growth rate of perturbation.

Stepwise target perturbation causes an impact to the actuator and rapid achievement of the saturation zone because of the "acute" reaction of the components of the PID controller, namely the proportional and differential parts. The Control Loop Foundation [4] recommends to make lower the rate of growth of the set point signal, namely, provide a linear (integral) transition to a new preset value for a predetermined time (1–2 s is recommended value). This method reduces the rate of imbalance growth and, as a consequence, the rate of change of the PID controller output signal. Disadvantage of this method is impossibility of eliminating the integral saturation caused by disturbances in the system and introduction of additional inertia into the regulation system.

It was decided to replace the linear (integral) limitation of the setpoint change rate (Fig. 8) in favor of passing the target signal through the first-order aperiodic link (Fig. 9). Implementation of the aperiodic link of the first order requires less processor resources and memory of the controller compared to the implementation of the integrated link but the system in this case has better properties of reducing the integral saturation.

The application of linear limitation of the target perturbation growth rate has reduced the ITAE of the transient process of regulation by

$$100\% \cdot \left(1 - \frac{8361}{8946}\right) \approx 6,5\%,$$

while the aperiodic limitation of the target perturbation growth rate has made it possible to reduce ITAE by

$$100\% \cdot \left(1 - \frac{8171}{8946}\right) \approx 8,7\%$$

in comparison with the PID controller without elimination of the integral saturation.

2. Prohibition of integration.

One of the methods for eliminating integral saturation consists in that the controller monitors magnitude of the control action on the object and once it reaches saturation, prohibition of integration (10) for the integral component of the controller is introduced (Fig. 10) [2, 5]:

$$e_i(u_c) = \begin{cases} 0, & (u_c \geq u_{max}) \vee (u_c \leq u_{min}), \\ e_c, & u_{min} < u < u_{max}, \end{cases} \quad (10)$$

where e_i is the input signal of imbalance to the integral component; e_c is the input signal of imbalance to the PID controller; u_c is the output of the PID controller (the control action); u_{min}, u_{max} are the desired maximum and minimum outputs from the controller.

Advantages of this method:

a) simplicity of program implementation;

b) reaction both to the change of the setpoint and the perturbation in the system.

The drawback: the problem of limiting the rate of the control signal growth is not solved. ITAE of the transient process of regulating rarefaction in the boiler unit furnace has decreased by

$$100\% \cdot \left(1 - \frac{8177}{8946}\right) \approx 8,6\%$$

in comparison with the reference experiment.

3. *Conditional integration.*

Conditional integration is development of the prohibition procedure of integration. The controller monitors magnitude of the control action on the object and as soon as this magnitude reaches saturation, functioning of the integral component of the controller is stopped. Conventionality consists in that the prohibition of integration comes not only in a condition of saturation but also in some other conditions, for example, when imbalance of the initial value or the rate of change of a certain predetermined value is achieved [5]. When these conditions are fulfilled, saturation of the controller is analyzed. If it increases, then prohibition of integration is introduced. Like in the method of integration prohibition, disadvantage consists in that it does not solve the problem of limitation of the rate of growth of the control signal.

4. *Compensation of saturation using the actuator model.*

With the actuator model, it is possible to trace its output signal and compensate the saturation effect by changing the signal applied to the integral component of the PID controller [5]. Use of saturation compensation by means of the actuator model at $T_s=3$ s (Fig. 12) has allowed us to reduce ITAE of the transient process of regulation of rarefaction in the boiler unit furnace by

$$100\% \cdot \left(1 - \frac{8115}{8946}\right) \approx 9,3\%$$

in comparison with the PID controller without elimination of the integral saturation. Disadvantage of this method consists in introduction of an additional parameter T_S to the structure of the PID controller to be regulated.

The conducted studies in the field of problems on integral saturation and the methodology of their solution have shown that there are many ways of this problem solution at present but each of the methods described above has both advantages and disadvantages. In order to achieve high qualitative indicators of elimination of the integral saturation during practical implementation of the PID controller,

it was decided to apply an integrated approach (Fig. 13), namely, the simultaneous implementation of limitation of the target perturbation growth rate and conditional integration (11). The chosen convention of the prohibition of integration is described by the dependence:

$$e_i(u) = \begin{cases} 0, \ u_c \in M, \\ e_c, \ u \notin M, \end{cases}$$

$$M = \left\{ \left[(u_c \ge u_{max}) \wedge (e_c > 0) \right] \vee \left[(u_c \le u_{min}) \wedge (e_c < 0) \right] \right\}, \quad (11)$$

where e_i is the input of the imbalance signal to the integral component; e_c is the input imbalance signal to the PID controller; u_c is the output of the PID controller (control action); u_{min}, u_{max} are the desired maximum and minimum outputs from the controller.

Both methods are simple in programming but their combining is a mutually beneficial symbiosis in solving the saturation problem since the conditional integration responds to the effects of external perturbations in the system but does not solve the problem of rate limitation. Also, the resulting structure is characterized by an interesting property: the block of limitation of the rate of the target perturbation growth does not enter into the control circuit, that is, it does not affect robustness and quality of the system's control. The reaction to noise and perturbation is only determined by a controller in which conditional integration is realized. Combining these two methods has allowed us to take advantage of the principle of open control and the principle of feedback control. As a result of the simultaneous implementation of the limitation of the target perturbation growth rate and the conditional integration, ITAE of the transient process of regulating rarefaction in the boiler unit furnace was reduced by

$$100 \ \% \cdot \left(1 - \frac{7955}{8946} \right) \approx 11,1 \ \%$$

in comparison with the PID controller without elimination of integral saturation.

The PID controller has modes when its parameters change in steps. For example, when it is necessary to change the target in the operating system, parameters of the controller settings or when there is a need to switch to the automatic mode after manual control of system [4]. In the described cases, if no special measures are taken, unwanted disturbances of the regulated quantity appear which leads to a decrease in the regulation efficiency.

The main method for solving the problem of stepped perturbation of the input parameters of the controller is integration of these signals which ensures a smooth change of the parameter and as a result, the output value of the controller [4, 5]. In the course of the study, it was decided to replace the linear (integral) attainment of the specified controller parameter (Fig. 8) in favor of passing the target signal through the first-order aperiodic filter (Fig. 9).

In the process of automatic control, situations often arise when it is necessary to change the mode of loop operation [4]. For example, when switching from automatic control to manual one, switching from the cascade system structure to a single-loop one, transition from the regulation mode to the setup mode, etc. The problem of nonimpact mode switching consists in that each of these modes has its own predetermined value that does not coincide with others. When switching from one mode to another, the actuator

or the installation in general is exposed to an "impact" (Fig. 14) resulting in unwanted disturbances in the system and, accordingly, excessive energy consumption to overcome these perturbations.

The main methodology for solving this problem consists in tracing the current state of the control action and its "copying" with other modes. Then, when switching from one mode to another, a smooth transition from the current system state to the specified one takes place (Fig. 14). Tracing of the current state and mode of the PID controller has allowed us to reduce ITAE of the transient process of regulating rarefaction in the boiler unit furnace by

$$100 \ \% \cdot \left(1 - \frac{11090}{13480} \right) \approx 17,7 \ \%$$

in comparison with the PID controller without taking into account the nonimpact switching of modes.

As a result of the conducted study, a coherent picture of the PID controller as a technically implemented element of the automatic control system has been formed taking into account technical limitations and real behavior of the control object. We can talk about expediency of the proposed solutions in the systems of automation of technological processes in various industries, including power, processing, chemical industries, objects of housing and communal services, etc.

All studies were conducted for one typical object of a certain class. Certainly, there may be a situation where other types of objects will differ in their results. This requires further studies and determination of the applicability limits of individual solutions.

7. Conclusions

1. It was established that the simultaneous application of an exponential filter of the measured value and a differentiator with a low-cut filter is optimal for practical realization of the PID-controller for inertial objects with a transportation lag. In addition, introduction of the zone of the controller insensitivity will potentially provide a longer actuator operation life.

2. It has been shown that nonlinearity of a "limitation of the rate of the change of the controller target" type affects dynamics of the transient process and the passage of the target signal through the aperiodic link of the first order yields a gain of 2 % in the reduction of ITAE criterion in comparison with the typical linear limitation.

3. It was determined that the greatest effect in the problem of eliminating the influence of integral saturation of the PID controller is achieved by applying an integrated approach: limiting the rate of growth of the target perturbation and conditional integration. Such a symbiosis of the methods eliminates shortcomings of each other and can reduce ITAE by more than 10 % compared to a system with no compensation for integral saturation.

4. It was shown that application of algorithms of nonimpact switching of operating modes of the controller, i. e. monitoring of the current state, positively influences dynamics of the control system. The effect of applying the algorithms depends on the instantaneous value of the difference between the current value of the control action and the expected value after a change of the mode. For the system under study, application of tracing of control action in various modes has resulted in a decrease in the qualitative criterion by more than 17 %.

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