AUTOMATED SETTING OF REGULATORS FOR AUTOMATED PROCESS CONTROL SYSTEMS IN THE SIMINTECH VISUAL MODELING SYSTEM

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For successful technological process in automated control systems it is necessary to maintain technological parameters constantly at the required level, which is ensured by the use of automated process control systems (APCS). The classical solution of this problem is the application of control devices of various types, the choice of which directly depends on the system under consideration and the requirements to it. The leading position among the automatic control system regulators for the last decades belongs to the proportional-integral-differentiating (PID) regulator, which efficiency of application in the technological process is defined by the speed and accuracy of its work. These qualities directly depend on the correct setting of the regulator parameters. The synthesis of regulators requires using of modern computer-aided design systems. The article presents the method of automatic setting of PID-regulator of the dynamic system of high order with negative feedback on the example of automatic room temperature control system. The modern Russian environment of dynamic simulation of technical systems SimInTech applied at a number of nuclear, oil refining and aerospace enterprises is used as the environment for system model development, as well as the process of its analysis and optimization. The main components of the system and transfer functions of its elements are presented. The step-by-step description of the process of project construction from standard software blocks and submodels, interacting through a single database with the use of built-in programming language, is described. The use of the built-in block of SimInTech visual simulation environment optimization for automated search of PID-regulator parameters is described in details and illustrated. The advantages and disadvantages of this adjustment method revealed during the project implementation are listed.

Keywords: modeling, PID-regulator, automatic control system, SimInTech.

АВТОМАТИЗИРОВАННАЯ НАСТРОЙКА РЕГУЛЯТОРОВ ДЛЯ АСУТП В СРЕДЕ ВИЗУАЛЬНОГО МОДЕЛИРОВАНИЯ SIMINTECH

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Для успешного протекания технологического процесса требуется постоянное поддержание технологических параметров на требуемом уровне, что обеспечивается применением автоматизированных систем управления технологическими процессами (АСУТП). Классическим решением данной задачи является применение управляющих устройств различного типа, выбор которых напрямую зависит от рассматриваемой системы и предъявляемых к ней требований. Лидирующую позицию среди регуляторов АСУТП последние десятилетия занимает пропорционально-интегрально-дифференцирующий (ПИД) регулятор, эффективность применения которого в технологическом процессе определяется быстродействием и точностью его работы. Данные качества напрямую зависят от правильности настройки параметров регуляторов, для синтеза которых необходимо использование современных систем автоматизированного проектирования. В работе рассматривается метод автоматизированной настройки ПИД-регулятора динамической системы высокого порядка с обратной связью на примере системы автоматического регулирования температуры в помещении. В качестве среды разработки модели системы, а также процесса ее анализа и оптимизации используется современ-

ная российская среда динамического моделирования технических систем SimInTech, используемая на ряде предприятий атомной, нефтеперерабатывающей и аэрокосмической отраслей. Приведены основные компоненты системы, передаточные функции ее элементов. Дано поэтапное описание процесса создания проекта из типовых блоков и субмоделей программного обеспечения, взаимодействующих через единую базу данных сигналов с применением встроенного языка программирования. Подробно описано и проиллюстрировано использование встроенного блока оптимизации среды визуального моделирования SimInTech для автоматизированного поиска параметров регулятора ПИД-типа. Перечислены выявленные в ходе реализации проекта преимущества и недостатки данного метода настройки.

Ключевые слова: моделирование, ПИД-регулятор, АСУТП, SimInTech.

Introduction. Design of control systems is an important component of modern technological production. For a long time regulators have been acting as the basis for managing technological processes. Their main task is to maintain the value of the system parameter at the level set by technology for the successful flow of the technological process as a whole. The choice of regulator type is diverse: from the simplest two-position to self-adjusting microprocessor regulators.

Traditionally, proportional-integral-differentiating (PID) regulators are used in process control systems. PID regulation is a fundamental element of the management process in continuous operation. PID-type control devices are widely used in the field of automation due to their longevity, flexibility, high functionality and reliability. PID-regulators are universal in application, suitable for solving most practical problems, they are easy to implement and have a low cost. Their applications range from household devices to nuclear and aerospace industries.

However, in practice a significant proportion of control problems are associated with incorrect configuration of PID-regulators: the accuracy and speed of the system as a whole depends on the correct setting of the regulator coefficients. It means that the task of parametric synthesis of control devices is an urgent task.

The task of parametric synthesis for the specified control objects is reduced to determining the optimal parameters of the regulator, which meet the required operating conditions of the system, as well as the requirements for the quality and accuracy of control.

Currently, a number of methods, algorithms and rules allows speeding up and simplifying the task of setting up regulators [1–4]. These methods are usually divided into two broad categories: methods aimed at ensuring the quality requirements of regulation, or selection methods, in which the system operator must match the desired operator as accurately as possible [5]. Recently, regulators that can calculate the "correct" parameters when the device is connected to the system have become very popular [6]. Some of the methods for setting up regulators were considered in previous works [7–9].

In this paper, we consider the process of automated search for parameters of a PID-type control device included in the control loop. The object of regulation is a heated room. The model of the automatic control system (ACS) of room temperature is implemented in the Russian environment of dynamic modeling of technical systems *SimInTech*.

The algorithm of PID-regulator work. The PID-regulator is a parallel connection of typical links of P-, I- and D-regulators [10]. The transfer function of a PID-regulator is the sum of the transfer functions of each type of regulator:

$$W_{PID} = K_p + \frac{1}{T_i \cdot p} + T_d \cdot p \; ,$$

where K_p – the regulator gain coefficient or the transmission coefficient; $K_i = \frac{1}{T_i}$ – the integration constant; $K_d = T_d$ – the differentiation constant.

There is no static error in PID-regulator system and they are of high performance. Regulators of this type provide a relatively high quality of regulation of objects that have a large transition delay (for example, heat exchange and mass transfer devices), as well as in cases where the load in the control objects changes frequently and quickly.

It should be noted that if the adjustment coefficients of the PID-type control device are set inaccurately, it might have worse indicators than the two-position regulator and even go into self-oscillation mode.

Automatic room temperature control system. In general, the automatic temperature control system in the room is shown in fig. 1.

The object of regulation in the system under consideration is a heated room. The indoor temperature θ is a controlled value; the air temperature θ_k coming from the heater is a regulating (controlling) effect; external factors f are a disturbing effect.

The sensing device (sensitive element) in this control system is a thermal resistor R_d included in the bridge circuit. The thermal resistor also performs the functions of a comparing device. An amplifier provides the amplification of the ΔU signal (mismatch signal) of the measuring bridge circuit. The amplified signal U_d provides rotation of the two-phase prime engine, which changes the amount of movement of the valve (flap) on the steam supply pipeline to the heater, which achieves a change in the air temperature at the outlet of the heater regulating the effect on the control object.

The initial data of the system is in [11]. The control system model has the following transfer functions:

$$W_r(p) = \frac{1}{400 \cdot p + 1} \; – \text{ transfer function of the object of}$$

regulation according to the regulatory effect;

$$W_d(p) = \frac{0.2}{400 \cdot p + 1} \; – \text{ transfer function of the object of}$$

regulation according to the disturbing effect;

$W_s(p) = 0.2$ – transfer function of the sensor;

$W_m(p) = \dfrac{10}{0.5 \cdot p + 1}$ – transfer function of a magnetic amplifier;

$W_e(p) = \dfrac{0.002}{p \cdot (0.08 \cdot p + 1)}$ – engine transfer function in conjunction with the valve;

$W_h(p) = \dfrac{10}{20 \cdot p + 1}$ – transfer function of the heater.

Main requirements for the quality of automatic control system. The main task of the regulator in the system under consideration is to maintain the technological parameter and the room temperature at a given level while minimizing the influence of external disturbing influences.

The system has the following requirements:

– working out the set value without an error in a settled mode;

– transition time – no more than 500 seconds;

– number of vibrations – no more than one, its amplitude should not exceed 5 % of the set value.

Simulation of ACS in the environment *SimInTech* and setting the coefficients of PID-regulator. The Russian SimInTech modeling environment was chosen as the system development environment for its analysis and optimization [12–14].

The initial complex dynamics model implemented in this software can be simplified. This provides verification of the basic principles of operation of the simulated object and its control system. As the design progresses, its individual parts can be refined and supplemented to match the real object in as much detail as possible.

To create a complex mathematical model, models of the main subsystems (submodels) implemented as separate projects are combined into a single package [15]. To link projects to each other, the signals database is used, which is a file database that contains all the necessary variables for the projects to work. These variables are used to describe the model, visually represent the modeling process on video frames, exchange data with external modules etc.

As a programming language, this software uses the built-in C language to write scripts that perform manipulations with schema objects as they are calculated.

The ACS scheme implemented in the *SimInTech* visual modeling environment is shown in fig. 2. The control object is placed in a submodel consisting of standard blocks, the composition of which is shown in fig. 3.

In the "calculation of transient parameters" submodel, which is shown in fig. 4, automatic calculation of time indicators of control quality is performed: the control time and the maximum of the controlled value. In the script, basing on the data obtained (the steady value and its maximum) the overshooting value is calculated.

The calculation of the control time – the time for which the value of the system reaches a new steady value is as follows: the mismatch signal module (control error) is applied to the middle (logical) input port of the key. Given that the complete process attenuation occurs at $t \to \infty$, the duration of the transition process is limited to the moment when the controlled value begins to deviate from the steady value by less than 5 %. Based on this, if the mismatch signal exceeds the specified five percent set point, the current model time (signal from the lower input port) is transmitted to the key output. If the control signal is less than the set point, the same signal is transmitted to the key output, but delayed by one integration step (the signal from the upper input port). Thus, after the calculation is completed, the variable «determining the control time» will contain the value of the transition time.

All variables calculated during operation are recorded in the signal database. An example of a project signal database is shown in fig. 5.

Detailed information about the database structure of the project (tab. 1).

In the *SimInTech* visual modeling environment, the PID regulator is represented by a separate block of the "Discrete" library – "Discrete PID-regulator". When implementing the ACS scheme with an embedded PID-regulator, shown in fig. 6, only the macroblock "Control object" is modified: the regulator, which parameter setting is the task of this work, takes place after the comparison device.
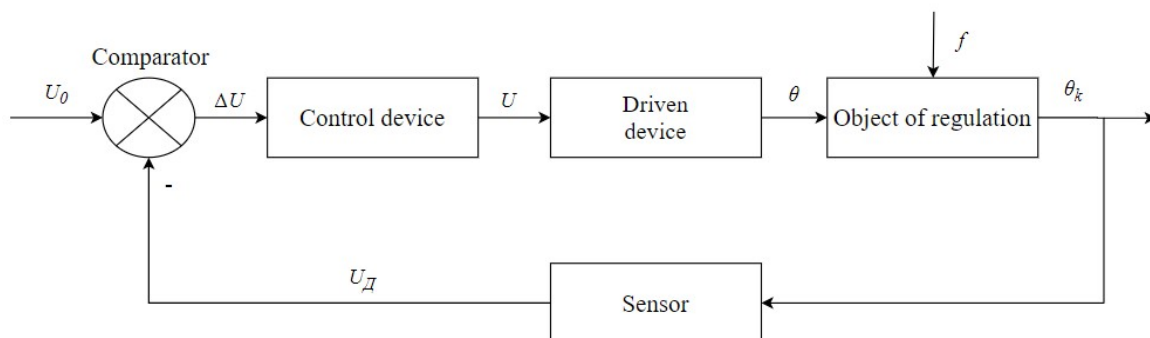

Fig. 1. Functional chart of automatic control system of room temperature

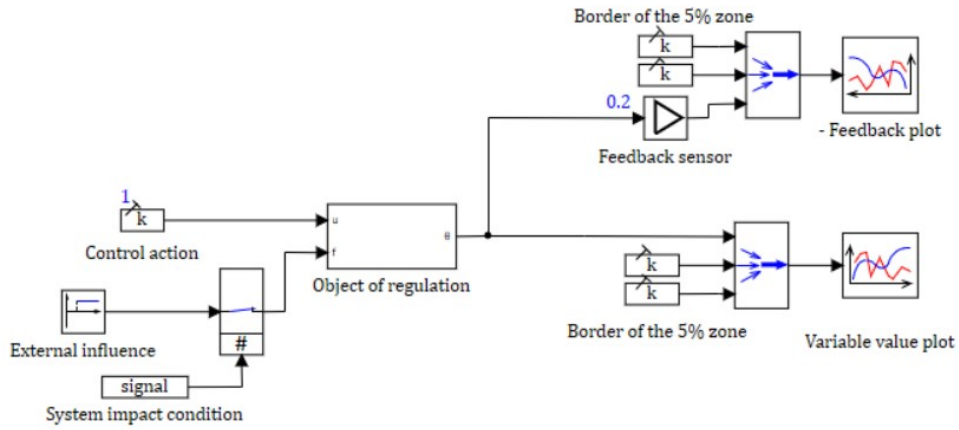Рис. 1. Функциональная схема САР температуры в помещении

Fig. 2. The automatic control system in the SimInTech environment

Рис. 2. Система автоматического регулирования, введенная в схемное окно SimInTech
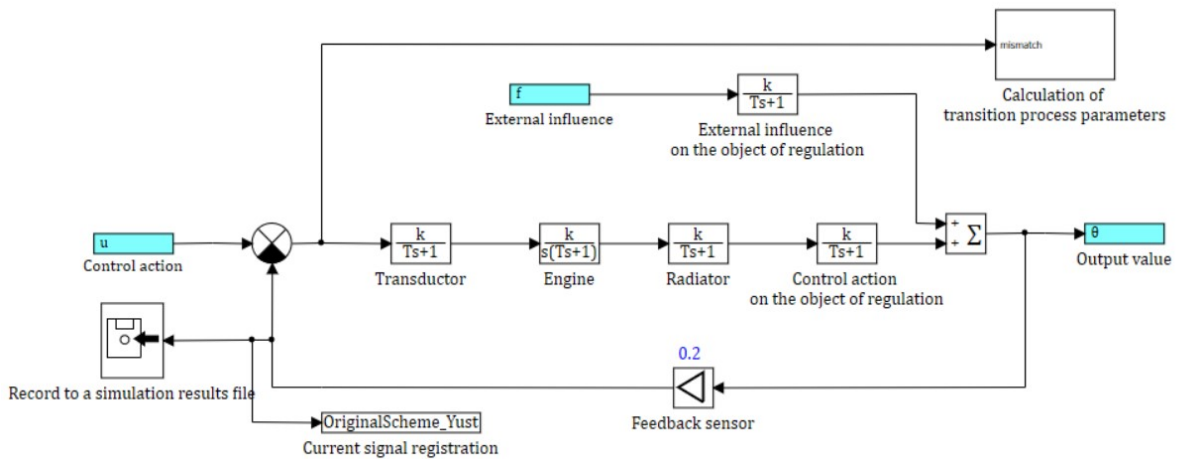

Fig. 3. Composition of the «Control object» substructure
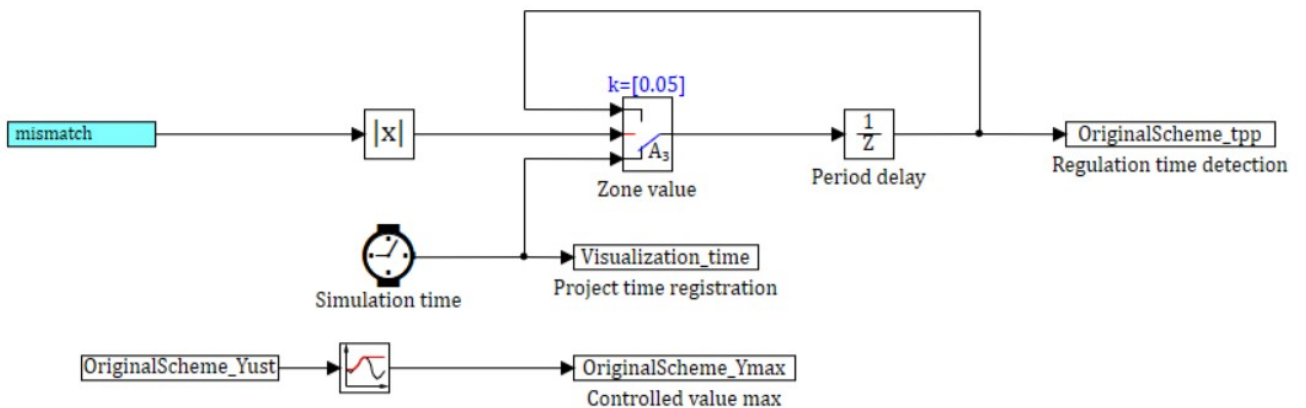
Рис. 3. Состав субструктуры «Объект управления»

Fig. 4. Composition of the substructure "Calculation of transition process parameters"

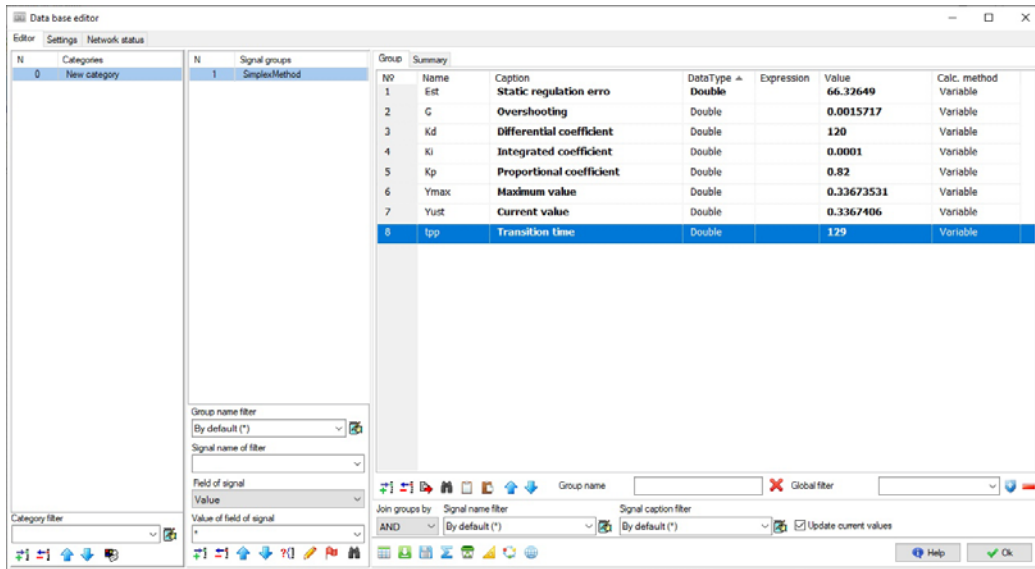Рис. 4. Состав субструктуры «Вычисление параметров переходного процесса»

Fig. 5 Design of the Signal Database of the Package
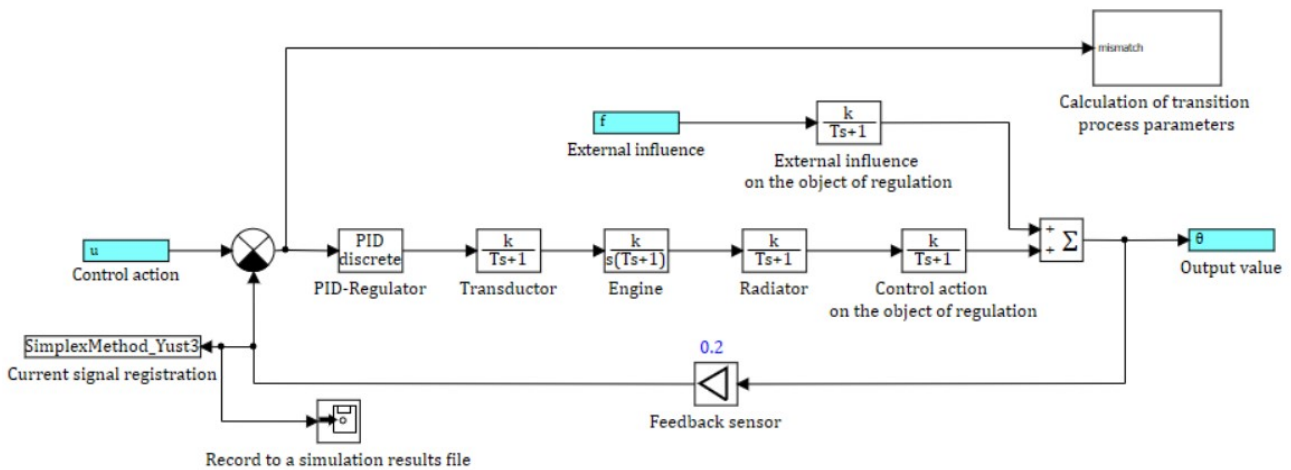
Рис. 5. Внешний вид базы данных сигналов пакета

Fig. 6. The automatic control system model with discrete PID regulator

Рис. 6. Модель САР с дискретным ПИД-регулятором

Table 1

The list of signals of the project database

Name	Caption	Data type
tpp	Transition time	double
$Y_{\max}$	Maximum value	double
Yust	Current value	double
Est	Statistic regulation error	double
G	Overshooting	double
K_p	Proportional coefficient of regulator	double
K_i	Integrated coefficient of regulator	double
K_d	Differential coefficient of regulator	double

The regulator block will be accessed via the signal database: for this purpose, the corresponding variable from the signal database is specified in the properties of the control device block opposite to each of the components of the PID-regulator. The values of the regulator coefficients will change automatically, which allows accessing this object from any project in the package.

In the dynamic environment *SimInTech* created a special block "Optimizer", located in the library "Analysis and optimization", which allows you to perform an automated search for such values of variable parameters of the ACS, in which the dynamic characteristics of the ACS (and the transition process, in particular) meet one or more conditions (criteria) "optimalities". The scheme of the system with the parameter optimization block is shown in fig. 7.

The following algorithms are used as optimization methods that can be implemented in this block [13]:

1) Search – 2: an algorithm for dividing the step in half for one optimized parameter ($n = 1$) and an algorithm for converting the direction matrix for ($n > 1$) is implemented. Next, we consider the multidimensional search algorithm.

2) Search – 4: implements a quadratic interpolation algorithm for one optimized parameter ($n = 1$) and an algorithm for rotation and stretch-compression transformations ($n > 1$).

3) Simplex method: the "deformable polyhedron" method of Nedler and Mead is used, in which a function of n independent variables is minimized using ($n + 1$) vertices of the deformable polyhedron. Each vertex can be identified by the vector x. The vertex (point) at which the value of $f(x)$ is maximal is projected through the center of gravity (centroid) of the remaining vertices. Improved (smaller) values of the objective function are found by sequentially replacing the point with the maximum value of $f(x)$ with more "good" points until the minimum of $f(x)$ is found.

The main task of using the "Optimizer" block is to correctly configure the required data, including:

– names of variable parameters, limits of their change and calculation error;

– names of local criteria and acceptable limits of their values;

– calculated optimization method and its settings.

Look at the process of configuring the parameters of the optimization block in details [13].

The optimization parameters are the transition time *tpp* and the maximum value *Ymax* during the transition process. Accordingly, the optimization should be calculated for the entire transition process, so in the "Parameter optimization mode" select "full transition process".

Using the properties "Maximum values of block outputs" and "Minimum values of block outputs", we limit the search range for optimal system parameters. The proportional and integral components will vary in the range [0.0001; 5], the differential – in the range [0.0001; 300].

In the "Absolute accuracy of selecting output values" property, we specify the accuracy when calculating the optimized parameters.

The "Initial increment of outputs" property sets the first increment step when selecting optimum values. The larger the step, the faster the selected values change at the beginning of the search for the optimum, but there is a chance that the optimal value will be skipped. Set a step equal to "Absolute accuracy of selecting output values», it slows down the calculation, but guarantees the search with the specified accuracy.

The "Minimum values of input optimization criteria" and "Maximum values of input optimization criteria" properties define the acceptable range of optimization criteria. According to the requirements imposed on the

system when setting the task for the synthesis of the regulator, the value of overshoot should not exceed 5 % of the set value, the transition time when working out the task should not exceed 500 s. Thus, the minimum values of the optimization criteria are as follows: $Y_{max} = 0.95$; $tpp = 0$ s. The maximum values of the optimization criteria are: $Y_{max} = 1.05$; $tpp = 500$ s.

The simplex method is chosen as the optimization method.

The "Initial approximation of outputs of the block" property sets the vector of initial values of the optimized parameters. In this case, the optimized parameters are the coefficients of the PID-regulator. Add approximate values of the regulator parameters calculated by the Ziegler–Nichols method to this property [16]. The result of configuring the properties of the "Optimizer" block is shown in fig. 8.

The setup procedure in the Ziegler-Nichols method has the following steps:

1. Experimental study of the system: the studied system with a given object of regulation is supplied with a proportional regulator, the gain coefficient K_p of which vary as long as at the output of the system the oscillations with constant amplitude are not set.

2. Fixing of values: the value of the transmission coefficient of the regulator, at which the system is at the boundary of stability and the period T^* of steady-state oscillations in the system, is fixed and denoted by K_p^*.

3. Values of the PID-regulator parameters are calculated using the formulas given in tab. 2.

This method is based on the use of data obtained experimentally on a real object and the use of stability reserves [15].

Experimental results of the study. The proportional coefficient $K_p^* = 1.242$ was determined experimentally, at which oscillations with a constant amplitude are established in the system. From the graph, we determine the oscillation period $T^* = 577$ s.

Required parameters of the PID-regulator, according to table 2 have the following values:

$K_p = 0.7450$;
$K_i = 0.0025$;
$K_d = 53.755$.

Add data to the properties of the «Optimizer» block and configure parameters using the built-in tools of the *SimInTech* environment.

Graphs of the transition process without the use of the controller and with the application controller of the PID type, the coefficients of which were obtained from calculations of the unit "Optimizer" is shown in fig. 9.

For better comparison of the quality of the transition process, the designed in the course of work indicators of quality of regulation are summarized in tab. 3.

Table 2

PID-regulator parameters

Type	K_p	K_i	K_d
PID-regulator	$0.60 \cdot K_p^*$	$\dfrac{1.2 \cdot K_p^*}{T^*}$	$0.075 \cdot K_p^* \cdot T^*$
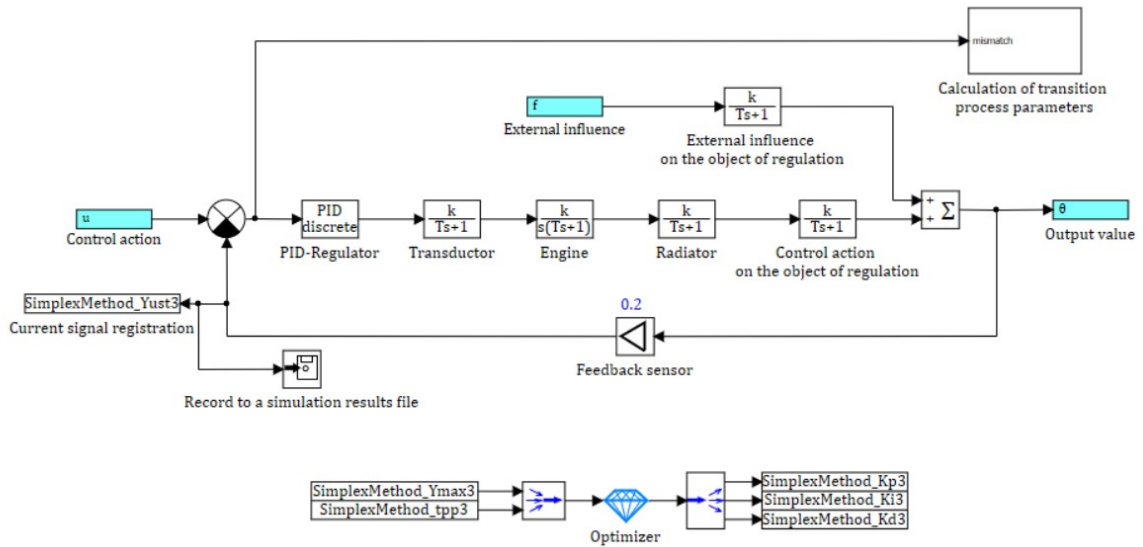
Fig. 7. The automatic control system model with optimizer

Рис. 7. Модель САР с оптимизатором

Fig. 8. Properties of the "Optimizer" block

Рис. 8. Свойства блока «Оптимизатор»

Table 3

Comparison of the quality of the transition process indicators

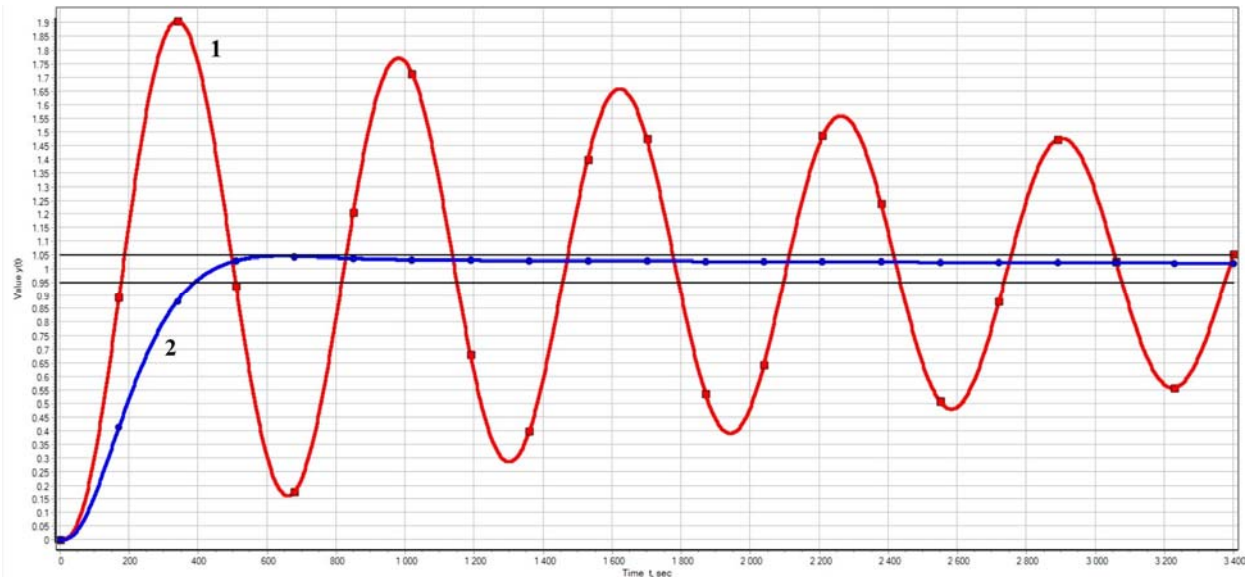| Parameter	Original scheme	PID-regulator scheme
Regulation time t_{reg}, s	11907	410
Maximum value Y_{max}	1.9	1.04
Second maximum value $Y_{max\,2}$	1.8	–
Overshooting σ, %	90.7	4
Attenuation D	0.11	1

Fig. 9. Comparison of the automatic control system transition diagrams,
where *1* is the original circuit, *2* is the circuit with the tuned PID regulator

Рис. 9. Сравнение графиков переходного процесса САР:
1 – исходная схема, *2* – схема с настроенным ПИД-регулятором

From the graphs of the ACS transition process and control quality indicators presented in fig. 9 and tab. 3, respectively, we can conclude that it is advisable to use control devices in technological process control systems. The automated search for controller parameters using the built-in *SimInTech* dynamic modeling environment fully meets the system requirements: the process parameter, in this case, the room temperature, is maintained at the set level, the set value is processed without error in the steady-state mode, the transition time is reduced compared to the original scheme and is less than 500 seconds, there are no fluctuations. The system is stable and efficient.

Automated adjustment of PID-regulator parameters using *SimInTech's* built-in tools has the advantage that the algorithm will work until it makes parameter settings that meet the required optimality criteria or, if this is not possible, selects such regulator coefficients so that the quality of system regulation is as close as possible to the required level. Moreover, several optimization methods are available, which allows to choose the best one for the designed system.

This method does not require the direct presence of the operator, it only sets the necessary operating conditions for the block, however, the configuration process can take a long time.

At the same time, the "Optimizer" in the *SimInTech* environment can be used to configure the parameters of control devices and dynamic systems of various types. The main thing is to set the optimality criteria and initial approximations of the output variables correctly.

Conclusion. In this paper, in the environment of dynamic modeling of *SimInTech* technical systems using standard blocks of general technical software libraries, a model of an automation object is developed and imple-

mented – a dynamic system with feedback on the example of an automatic temperature control system in a room. The application of such development environment tools as a database and a programming language is described.

The system includes a proportional-integral-differentiating regulator, which is a parallel connection of P-, I- and D-regulators in the form of a single block "Discrete PID-regulator".

An automated search for PID-regulator parameters was performed using the built-in tools of the development environment – using the "Optimizer" block, a detailed description of the application and settings of which is described in this paper. The advantages and disadvantages of the configuration method identified during the project implementation are described.

The results of the ACS simulation, as well as the system with the control device, are confirmed by time graphs and mathematical calculations. The quality indicators of the system control process are compared based on the following indicators: control time, maximum value of the controlled value, overshoot, attenuation.

Based on the results of system modeling, the feasibility of using *SimInTech* tools to determine the coefficients of a PID-type control device was evaluated. Conclusions are made about the effectiveness of this method: the system meets the requirements for it in full. It is possible to use the *SimInTech* model parameter optimization block for dynamic systems of different orders and control devices of different composition from the one under consideration.

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