DOI: https://doi.org/10.15276/aait.04.2019.7
UDC 62-503.57

SETTING REGULATOR PARAMETERS IN A PROGRAMMABLE LOGIC INTEGRAL CIRCUIT FOR AUTOMATIC CONTROL SYSTEMS OF HEAT EXCHANGERS

Vladimir V. Vychuzhanin
ORCID: https://orcid.org/http://orcid.org/0000-0002-6302-1832, vint532@yandex.ua
Odessa National Polytechnic University, 1, Shevchenko Avenue. Odesa, 65044, Ukraine

ABSTRACT

The article presents the results of the synthesis of digital controllers for automatic control systems of heat exchangers of central air conditioning systems, functioning under variable significant disturbing influences. The developed regulators are designed to provide the specified quality of regulation (short regulation time, permissible value of regulation), changes in the settings of the regulators taking into account the operating conditions of the regulatory object. The circuitry of regulators should be relatively simple. The requirements for the developed controllers are implemented in a typical digital PID-controller with optimization of its settings using the differential evolution algorithm. To assess the quality of PID-regulation, the regulator was tested in the ModelSim program. Test results were analyzed using Matlab. In order to implement the requirements for the developed regulators as an alternative to the PID-regulator with optimization of its settings using the differential evolution algorithm, a combined automatic control system based on the P-regulator has been created. The control system contains a P-controller with a synthesized corrective link, providing control by the deviation of the controlled variable from its predetermined value and by the perturbation applied to the controlled variable. Assessment of the quality of regulation of the P-regulator with the corrective link was carried out according to the results of research at Matlab. PID-controller with optimization of its settings using the differential evolution algorithm, as well as P-controller with corrective link is implemented in FPGA. The main language for describing the hardware for implementing regulators in FPGAs is the language for high-speed integrated circuits (VHDL). A comparative analysis of the results of a study of a digital PID-controller with parameter optimization and a combined automatic control system made it possible to establish that the controllers satisfy the required regulatory quality in the automation of heat exchangers in central air conditioning systems that are subject to significant disturbances. They have the ability to change settings taking into account the operating conditions of the regulatory object. It was found that the use of a P-controller with a synthesized corrective link, which has a simpler circuit solution, allows us to provide better control quality indicators in comparison with a PID-controller with optimized settings.

Keywords: Digital PID-Controller; Differential Evolution; Combined Automatic Control System; Programmable Logic Integrated Circuit; Heat Exchanger

***For citation*: Vladimir V. Vychuzhanin. Setting Regulator Parameters in a Programmable Logic Integral Circuit for Automatic Control Systems of Heat Exchangers. *Applied Aspects of Information Technology*. 2019; Vol.2 No.4: 328–344. DOI: https://doi.org/10.15276/aait.04.2019.7**

INTRODUCTION

The problem of high-quality control of objects operating under variable significant disturbing influences is one of the important ones that must be taken into account when developing appropriate automatic control systems (ACS) [1, 2], [3, 4].

The main requirements for the developed controllers of similar self-propelled guns are to ensure the specified quality of regulation (short regulation time, permissible amount of regulation), the possibility of changing the controller settings taking into account the operating conditions of the control object, as well as the relative simplicity of the circuit design of the regulators.

Incorrect adjustment of the parameters of the regulators can lead to cyclical and slow recovery, poor stability and loss of controllability of the control object.

Known methods for adjusting controller parameters include Ziegler-Nichols, Chin-Hrones-Resvik, Cohen-Kuhn and other methods [5, 6]. Most of these methods are applicable to both continuous and discrete control systems.

The experimental methods for tuning regulators proposed by Ziegler-Nichols, Cohen-Kun is based on trial and error methods. However, when using these methods, problems may arise when adjusting controllers, for example, for nonlinear objects of high order, in the presence of time delays, nonlinear processes in the control system.

To overcome these problems, various methods are used to obtain rational settings for regulators, including methods based on the use of evolutionary calculations – the genetic algorithm (GA) and differential evolution (DE) [7, 8], [9].

Genetic algorithms are heuristic search methods that are used to solve optimization and modeling problems by randomly selecting, combining, and varying the desired regulator settings. Deficiencies in GA: false convergence, loss of the best solution found, lack of support for the optimal value. In addition, GA does not always show good performance in solving nonlinear problems, as well as complex linear problems [10]. Therefore, at present, differential evolution is increasingly used to obtain rational tuning parameters for regulators.

Differential evolution is a stochastic method of multidimensional optimization, using the ideas of genetic algorithms to find the extremum of undifferentiated, nonlinear, multimodal functions. Unlike GA, which uses binary coding to represent the parameters of a task, DE uses real coding of floating point numbers. The main feature of DE is the use of the scheme for generating vectors of test parameters. Essentially, DE adds the weighted difference between the two population vectors to the third vector.

Typically, the DE [11] implementation needs three parameters: CR (defining mutually exclusive crossover and mutation operations); F (scaling factor of the difference of two individuals); NP (population size). For generating the evolutionary process for the n-dimensional problem.

The DE algorithm is simple, and its performance is comparable or even superior to GA [12, 13]. Based on the listed advantages of DE, such an algorithm can be chosen to optimize the settings of the object control regulators that function under significant disturbing influences.

Adjusting the parameters of the regulator used for the quality control of the objects functioning under the variables of significant disturbing influences can also be carried out when it is equipped with a standard regulator with corrective links. It is known that combined automatic control systems (ACS) are distinguished by the relative simplicity of the circuit design and are not inferior in quality of regulation (minimum regulation time, maximum overshoot or maximum dynamic error, static error, degree of attenuation) to systems, for example, with PID controllers during automation of objects subject to significant controlled disturbances [14, 15], [16].

It is possible to implement the parameter settings of digital controllers taking into account the operating conditions of the control object in programmable logic integrated circuits (FPGAs).

The development of FPGAs allows the implementation of digital controllers with variable settings with minimal material costs and reduced design time. Manufacturers offer a variety of FPGAs: programmable simple, matrix, and complex logic devices (SPLD, PAL, CPLD); user-programmable basic matrix chips (FPGAs) [17, 18].

Currently, FPGAs are widely used in developing hardware applications using intelligent computational methods in the design of digital control systems [19, 20]. A digital self-propelled gun on FPGA has features that distinguish it from analog systems: control laws are implemented in the form of algorithms programmed using hardware or software; quantized (time-discrete) signals are processed [21, 22], [23].

FPGA families allow you to implement evolutionary algorithms, starting from a dedicated system on only one chip and ending with an FPGA cluster [24, 25] to perform parallel computing, which can be useful for various applications.

The DE method allows real-time numerical optimization of controller settings. DE is suitable for accurately minimizing the numerical parameters of regulators. Moreover, FPGAs are desirable devices for use because of their massive parallelism [26, 27].

In [28], the PID controller was studied using its fixed-point representation in the FPGA program. Performance is compared to a floating point view with a fixed point view.

The fixed-point representation was evaluated using word length analysis methods. It was found that the fixed-point representation saves significant resources in the FPGA circuit (power loss and power consumption, reduce development time).

The DE algorithm, by its nature, always uses floating point encoding and several generations of random numbers.

Therefore, when implementing DE on FPGA, it is necessary to implement several random number generators in FPGA.

From [9], [25] it follows that the issues of optimizing the settings for PID-controllers implemented in FPGA using the DE algorithm are not sufficiently reflected from the point of view of evaluating the stability of the controllers in real time with minimal root mean square and integral absolute errors.

An analysis of literature also showed that an alternative to the developed PID-controllers, to optimize the settings of which, for example, DE is used, can be the development of combined digital automatic control systems that operate in real time and are distinguished by the relative simplicity of the circuit solution and not inferior in quality control systems with PID-controllers with DE settings [14, 15].

Thus, the search for new circuit solutions and principles for the operation of self-propelled guns to ensure a given quality of control of objects operating under variable significant disturbing influences involves the further development and research of PID-controllers with optimization of settings with DE, the creation and study of combined digital ACSs, followed by comparative analysis results of their application.

PURPOSE OF THE ARTICLE

The purpose of the article is to ensure the stability of regulators in real time with minimal regulation time and the amount of regulation during automation of objects subject to significant disturbances.

RESEARCH OBJECTIVES

1. Development and research of a digital PID controller in FPGA with optimization of settings based on DE.
2. Development and research of combined digital ACS in FPGA.
3. A comparative analysis of the quality of regulation of the developed PID-controller with optimization of settings based on DE and combined digital ACS implemented in FPGA.

As an automation object (Fig. 1), a heat exchanger (air heater) of the central air conditioning system (CACS) was selected, which functions under variable significant disturbing influences. Such systems differ in performance, control functions, and the amount of energy consumed [29-31].

The energy efficiency of CACS depends on how adaptive its regulators are to changes in environmental conditions and ensure that technological parameters are maintained with a given accuracy in real time with minimum control time, minimum control errors Controlled parameters of CACS are, for example, air flow controlled by an adjustable fan speed, heat and coolant costs to heat exchangers.

For this control object, due to the nonlinearity of the characteristics of the units, the process of adjusting the control parameters of the regulators is a laborious task.

The characteristics of the air heater determine the processes of heat treatment of air in the air conditioner; affect the choice of control actions and the quality of transients in the control system used. The thermal processes occurring in the heat exchanger are characterized by the distribution of parameters and therefore their dynamics is described in the general case by a nonlinear system of equations [31].

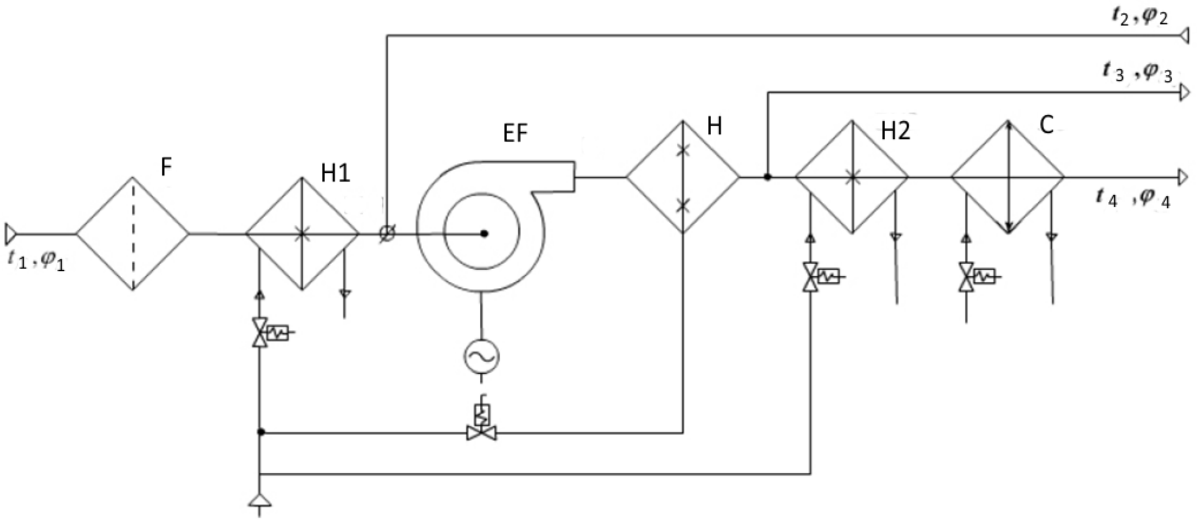

Fig. 1. **The structural diagram of the CACS:**
F – filter; H1, H2 – heaters of the first and second stages; EF –electric fan; H – humidifier; C – cooler
***Source*: compiled by the author**

In air heaters, the disturbing effects are the temperature and relative humidity of the air at its inlet.

The control actions can be steam flow or steam temperature at the inlet, air flow (if the device operates at a variable flow rate).

The regulators used to maintain the specified parameters at the output of the heat exchangers of the central CACS implement P, PI and PID-control laws.

However, in conditions of variable significant disturbing influences, regulators do not provide the required quality of regulation.

The parameters of the regulators need to be adjusted, which is not always possible to perform in the operating conditions of hard currency.

When developing controllers with tunable settings, the mathematical model of the air heater (H1; H2) [31], selected as an automation object, was taken into account.

DEVELOPMENT OF A DIGITAL PID-CONTROLLER IN FPGA WITH OPTIMIZATION OF SETTINGS BASED ON DE

The optimization of the PID-controller settings was carried out in accordance with the algorithm of its functioning and the DE algorithm (Fig. 2).

In accordance with the DE algorithm [32], a set of solutions (population) is used, and at each step they are transformed by successive application of selection operations, mutation crosses.

The objective function when optimizing the settings of the PID-controller in accordance with the DE algorithm

$$\min\ f(x) = f(x_1, x_2,..., x_n), \qquad (1)$$

where: x is an n-dimensional vector and f is a real function of real arguments.

For DE, the required population size (NP) is used [33] NP = 10 × D, where D is the population number, the crossover constant (CR) is $CR \in [0,1]$, the weight applied to the random differential (mutation coefficient) (F) – $F \in [0,5;\ 1]$ and the number of chromosomes to match the control parameters of the regulator.

The population is initialized by the generation of random individuals from 1 to NP chromosomes evenly between 1 and D. The difference vector is randomly generated from an individual choice.

The weighted difference vector is formed from the difference vector multiplied by the weight coefficient of mutation F.

The digital structure of the PID-controller is implemented at the module level. The mutation coefficient constant is affected by the length of the mutation step. With a decrease in the difference vector, the length of the mutation step in the population also decreases. A vector is born from the sum of the difference vector parameter and the individual parameter. The target vector intersects with the difference vector. Generational crossover is performed between the CR crossover parameter and a random number for each chromosome. Subsequently, the target and test vectors were selected based on the value of the objective function to place the target vector chromosomes by generations. The selection is made in accordance with the objective function. At least one chromosome is selected from the mutation vector. If the target vector is equal to the test vector, then the test vector is selected to continue in the genus.

Unsigned optimized parameters are imported from the DE optimization into the PID-controller. Proportional, integral and derivative components are calculated separately in the corresponding software modules.

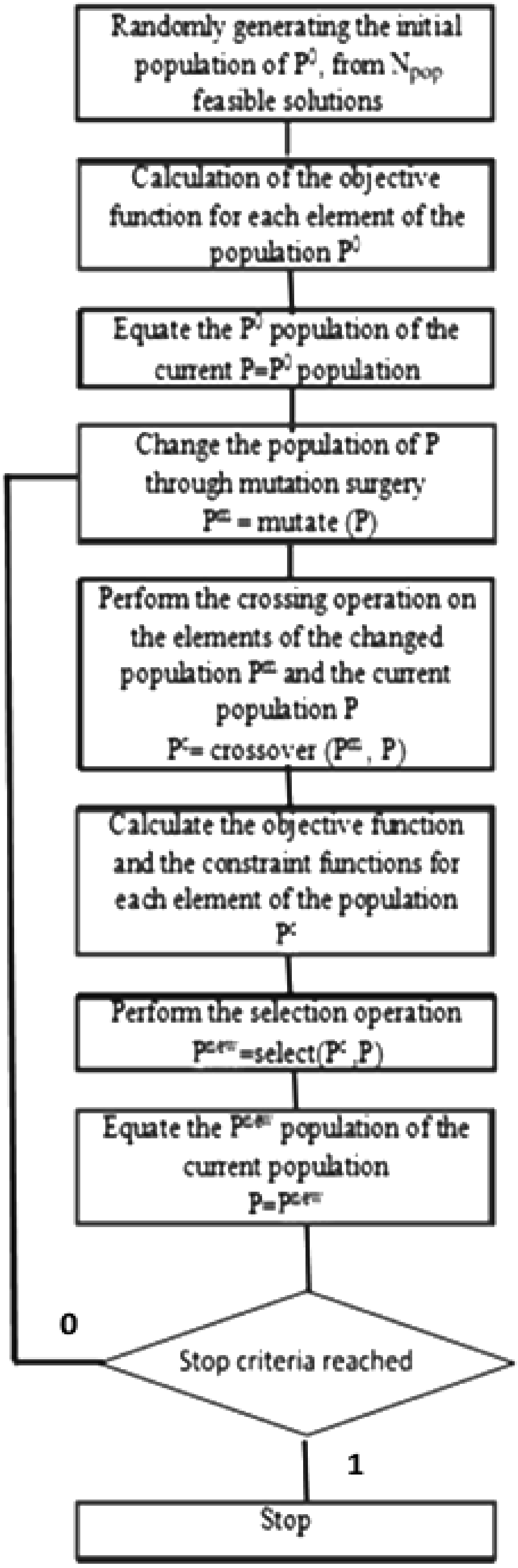

Fig. 2. **Differential evolution algorithm**
***Source*: compiled by the author**

The output value of the PID-controller is obtained by summing all terms. Optimization of the

The parameters of the PID-controller are selected by comparing the suitability values of different generations.

According to the suitability value for the PID-controller, the best control parameters are selected.

The functional diagram of the digital PID-controller with DE is shown in Fig. 3.

Digital PID-regulator traditionally described

$$\frac{U(z)}{E(z)} = \frac{b_0 + b_1 \cdot z^{-1} + b_2 \cdot z^{-2}}{a_0 + a_1 \cdot z^{-1} + a_2 \cdot z^{-2}} \quad (2)$$

The recurrent procedure for calculating the control corresponding to the operation of the digital PID controller taking into account [9] has the form

$$u[n] = k_1 \cdot u[n-1] + k_2 \cdot u[n-2] - k_3 \cdot e[n] - k_4 \cdot e[n-1] - k_5 \cdot e[n-2] \quad (3)$$

The scheme of the PID-controller integrated into the FPGA usually consists of register blocks (REG_1-REG_4) used to store current and previous PID-controller is realized by reducing the reference and measured values or the number of generations.

error values (E (n), e(n - 1), e(n - 2), u(n - 1) and u (n - 2)), adder (ADD) and multipliers.

The block diagram of the PID-controller in FPGA obtained in accordance with (3) and taking into account [34] is shown in Fig. 4.

To configure the PID-controller parameters, the DE2 (Altera) debug board was used [35]. DE is hardware implemented in the PMem memory module and the FXMem module for storing fitness function values, random number generators, and a state machine for controlling the DE execution sequence (Fig. 5).

The memory size is determined by the population size parameter NP and dimension D.

The FXMem module is implemented similarly to PMem, with the difference that the FXMem size is determined only by the NP parameter, since the individual stores only one value.

DE parameters when tuning the PID-controller to FPGA: NP = 100; CR = 0.9; mutation constant F = 0.6; the number of generations G = 50. D is set based on the number of parameters used in the objective function.

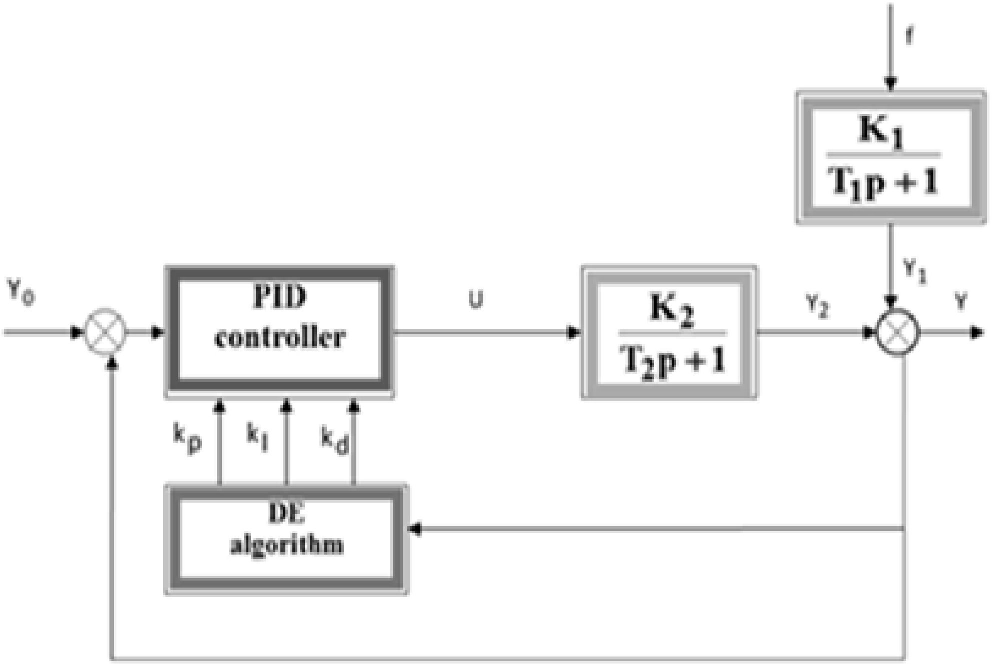

Fig. 3. **The functional diagram of the digital PID controller with DE**

***Source*: compiled by the author**

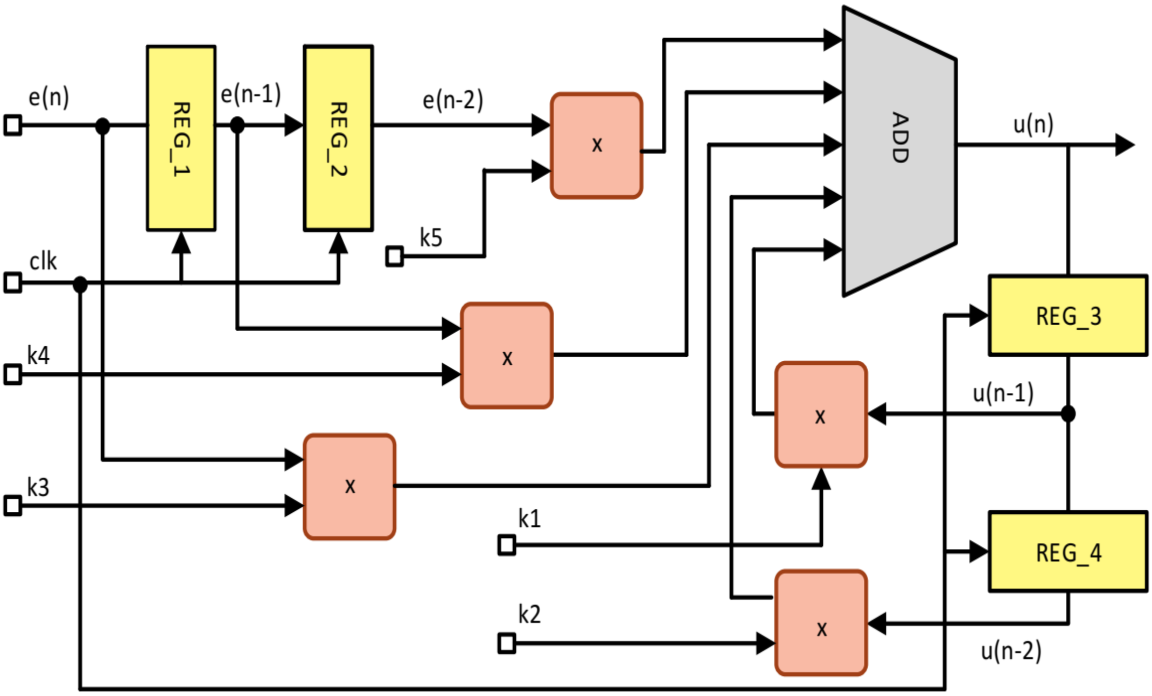

Fig. 4. **Block diagram of the PID controller in FPGA**
***Source*: compiled by the author**

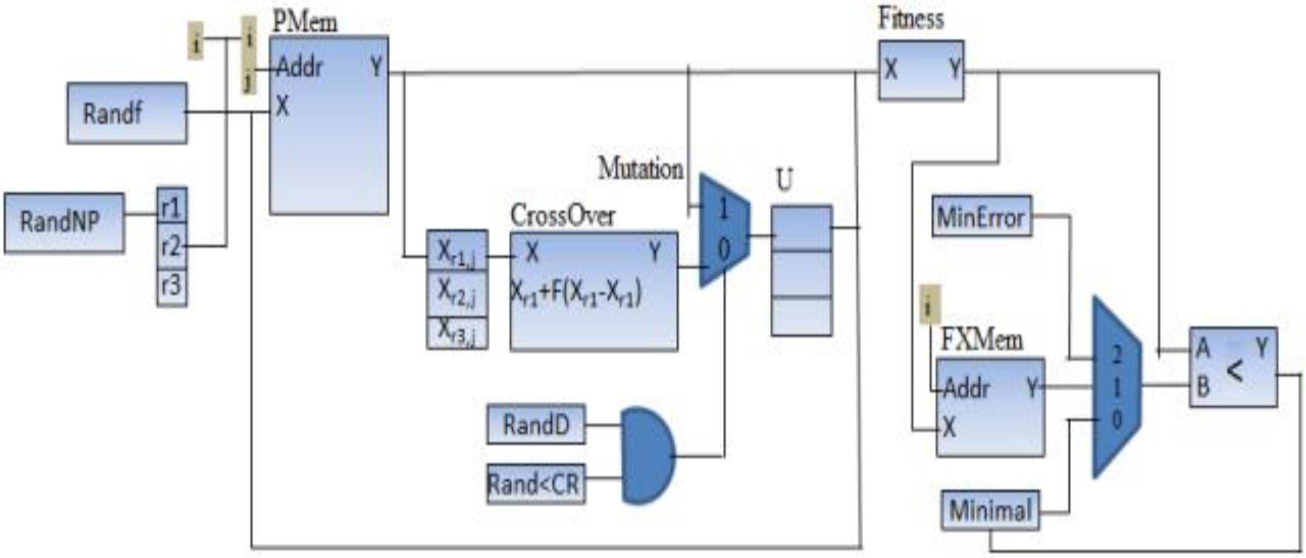

Fig. 5. **Hardware implementation of DE for configuration in FPGA**
***Source*: compiled by the author**

The resources of the FPGA program used for EP4CE115F29C7 (Cyclone IV E) are determined depending on the number of logic elements (4985), inputs (71), registers (1512), and multipliers involved.

The hardware description language VHDL is used as the language for describing the hardware of the PID-controller.

Synthesis of Combined Digital ACS in FPGA

The synthesis of the regulator is based on the methods used in the analytical design of combined ACS, taking into account the dynamic properties of the technological equipment of the central air conditioner CACS [31].

In order to compensate for the disturbing effects, ACS synthesis was carried out using the direct Lyapunov method.

To solve this problem, a function has been compiled that minimizes the difference between the disturbing signal and the control action of the form

$$I = 0.5 \cdot (U_1 - K_1 \cdot f)^2, \tag{4}$$

where: U1 is the control action compensating for the disturbing effect f;

K1 is the gain of the object.For continuous functions, the rate of change of the minimizing function (*I*) is determined by the formula

$$\frac{dI}{d\tau} = \frac{\partial I}{\partial f_1} \cdot \frac{df_1}{d\tau} + \frac{\partial I}{\partial f_2} \cdot \frac{df_2}{d\tau} + \ldots + \frac{\partial I}{\partial f_n} \cdot \frac{df_n}{d\tau} = gradI \cdot \bar{f} \tag{5}$$

The scalar product of the n-dimensional state vector of an object characterizing the change in *I* at time τ

$$\frac{dI}{d\tau} = \begin{vmatrix} \frac{\partial I}{\partial f_1} \\ \frac{\partial I}{\partial f_2} \\ \vdots \\ \frac{\partial I}{\partial f_n} \end{vmatrix} \cdot \begin{vmatrix} \frac{df_1}{d\tau}, \frac{df_2}{d\tau}, \ldots, \frac{df_n}{d\tau} \end{vmatrix} \tag{6}$$

The scalar product modulus (6) is maximal for parallel vectors $\bar{I}$ and и $\bar{f}$. There is proportionality between the components of the vectors (proportionality coefficient ρ, sec-1). Then, taking into account the search for the minimum of the function *I*

$$\frac{df_1}{d\tau} = -\rho \cdot \frac{\partial I}{\partial f_1}, \frac{df_2}{d\tau} = -\rho \cdot \frac{\partial I}{\partial f_2}, \ldots, \frac{df_n}{d\tau} = -\rho \cdot \frac{\partial I}{\partial f_n}; \tag{7}$$

$$\frac{d\bar{f}}{d\tau} = -\rho \cdot gradI \tag{8}$$

Given the non-stationary caused by the change in *f* over time

$$\frac{d\bar{f}}{d\tau} = -\rho \cdot gradI + \frac{\partial I}{\partial \tau}. \tag{9}$$

$$\frac{dI}{d\tau} = gradI \cdot \bar{f} + \frac{\partial I}{\partial \tau}. \tag{10}$$

For an automated regulatory object

$$\frac{dI}{d\tau} = (U_1 - K_1 \cdot f) \cdot \dot{U}_1 - (U_1 - K_1 \cdot f) \cdot \dot{f} \cdot K_o \tag{11}$$

The defining differential equation describing the control action, the compensating perturbation effect takes the form

$$\dot{U}_1 = -\rho \cdot (U_1 - K_1 \cdot f) \tag{12}$$

Lyapunov function (4) after substituting (12) in (11)

$$\frac{dI}{d\tau} = -0.5 \cdot \rho \div (U_1 - K_1 \cdot f)^2 - 0.5 \cdot (U_1 - K_1 \cdot f) \cdot \dot{f} \cdot K_1 \tag{13}$$

The stability condition is determined by the following inequality

$$\left| \rho \cdot (U_1 - K_1 \cdot f)^2 \right| > \left| (U_1 - K_1 \cdot f) \cdot \dot{f} \cdot K_1 \right| \tag{14}$$

Therefore, the function that minimizes the difference between the disturbing signal and the control action of the form (4) is the Lyapunov function when condition (14) is satisfied. In this case, the conditions must be met

$$I \geq 0; \quad \frac{dI}{d\tau} < 0. \tag{15}$$

Given the control action (y_0), function (4) and the control action U_1 are determined

$$I = 0.5 \cdot (U_1 - K_1 \cdot f - y_o)^2 \tag{16}$$

$$\frac{dU_1}{d\tau} = -\rho \cdot (U_1 - K_1 \cdot f - y_0), \tag{17}$$

where: y_0 is the specified value of the regulation parameter

To stabilize the air parameters at the outlet of the technological apparatus (air heater) of the air conditioning system, an air conditioner is proposed to use a regulator with P-control law in feedback. Then the second control action is determined

$$U_2 = -K_p \cdot \Delta y, \tag{18}$$

where K_p is the transfer coefficient of the P - controller;

Δy deviation of the value of the adjustable parameter y from its predetermined value y_0

Total control action at the output of the combined controller

$$U = -\rho \int_{\tau_o}^{\tau} (U_1 - K_1 \cdot X - y_0) dt - U_2 \qquad (19)$$

The block diagram of the developed ACS for a heat exchanger is shown in Fig. 6.

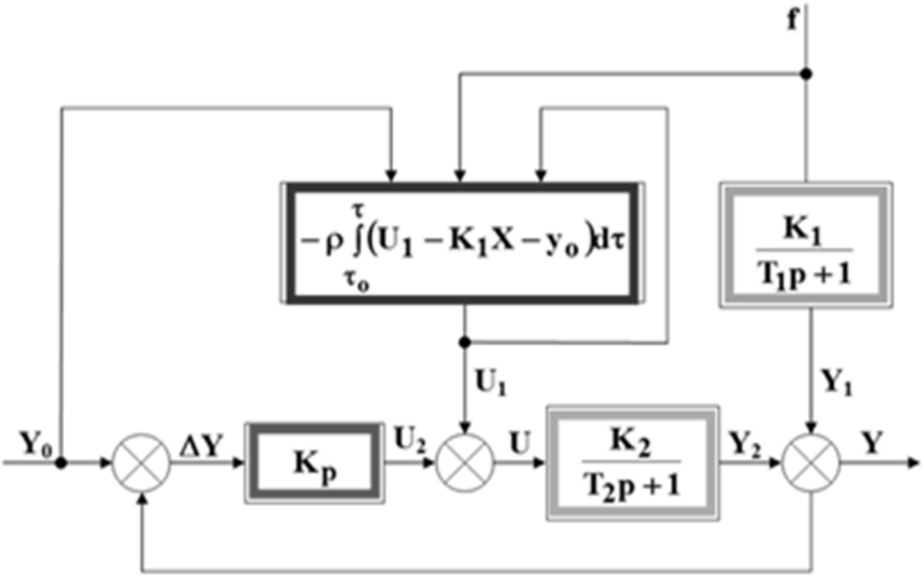

Fig. 6. **Structural diagram of a combined ACS of a central air heater**

***Source*: compiled by the author**

For small quantization periods, a digital control algorithm written in finite differences taking into account the increment of the control signal from the correction link

$$u_1(k) - A \cdot u_1(k-1) = B \cdot f(k) + C \cdot y_0, \qquad (20)$$

$$\frac{du_1}{d\tau} = -\rho \cdot (u_1 - K_1 \cdot f - y_0 \cdot M), \qquad (21)$$

where $A = \frac{1}{1 + T_k \cdot \rho}$; $B = \frac{T_k \cdot \rho \cdot K_{01}}{1 + T_k \cdot \rho}$; $C = \frac{T_k \cdot \rho \cdot M}{1 + T_k \cdot \rho}$;

M is a scale factor;

k = 1, 2, 3, ... the number of the quantization period

The algorithm of the digital P-controller that forms the control action is easy to derive using [34]

$$u_2(k) = K_p \cdot e(k), \qquad (22)$$

where: e(k) = y(k) - y_0 is the deviation of the output variable from the given value

In accordance with (20) and (22), in the combined digital ACS, a control action is applied to the executive body of the regulatory object (RO)

$$u(k) = u_1(k) + u_2(k) \qquad (23)$$

The algorithm of the entire control system when using the digital module RO

$$\begin{gathered} y(k) = a_1 \cdot y_1(k-1) + b_1 \cdot f(k) + a_2 \cdot y_2(k-1) + b_2 \cdot u_1(k); \\ e(k) = y(k) - y_0; \\ u(k) = K_p \cdot e(k) + A \cdot u_1(k-1) + B \cdot f(k) + Cy_0; \\ \Delta y(k-1) = \Delta y(k); \\ e(k-1) = e(k); \\ u(k-1) = u(k) \end{gathered} \qquad (24)$$

where: $a_1 = -\exp(-T_k / T_1)$; $b_1 = K_1 / T_1$;

$a_2 = -\exp(-T_k / T_2)$; $b_2 = K_2 / T_2$;

T_k – quantization period (according to Ziegler-Nichols $T_{к} = 0.1 \cdot T_{кр}$), sec;

K_1, K_2 – respectively, the transmission coefficients of the perturbing and control actions;

T_1, T_2 -_ respectively, the time constants on the transmission channels of the perturbing and control actions of the RO, sec

The developed scheme of the digital combined controller is implemented in FPGA, designing the device in Quartus II CAD.

Software VHDL – a description of the operation algorithm of the local combined digital controller

```
entity Reg is
     port
     (
       Clk: in bit;
       Io: in integer range -5000 to 172845;
       I: in integer range -5000 to 172845;
       Ik: in integer range -127 to 127;
       Result: out integer
     );
     end Reg;
architecture struct of Reg is
constant A: integer:= 0740;
constant B: integer:= 3898;
constant C: integer:= 9260;
constant Kp: integer:= 986000;
signal w: integer;
signal w1: integer;
signal w2: integer;
signal w3: integer;
signal w4: integer;
signal w5: integer;
signal Tmp: integer;
begin
  process(Clk)
  begin
    if(Clk'event and Clk = '1') then Tmp<=w5;
    end if;
  end process;
  process(Ik)
  begin
    w<=Ik*B;
  end process;
  process(Io)
  begin
    w1<=Io*C;
  end process;
  process(Tmp)
  begin
    w2<=Tmp*A/1000;
  end process;
  process(Io, I)
  begin
    w3<=Io-I;
  end process;
  process(w3)
  begin
    w4<=w3*Kp;
  end process;
  process(w, w1, w2)
  begin
    w5<=w + w1 + w2;
  end process;
  process(w4, w5)
  begin
    Result<=w4 + w5;
  end process;
end struct;
```

INVESTIGATIONS OF THE DIGITAL PID-CONTROLLER IN FPGA WITH OPTIMIZATION OF SETTINGS BASED ON DE

The study of the quality of regulation of the PID-controller is carried out by modeling in MATLAB. The results of studies for DE using the standard error and integral absolute error as the objective function for optimizing the settings of the PID-controller are shown in Fig. 7, obtained by changing the step perturbing effect on the heat content of air in front of the RO.

When modeling, we used the previously obtained data for the CACS air heater [31]: transmission coefficients K_1= 0.421+0.06; $K_2 = 0,813 \pm 0,17$ kJ / (kg %); time constants T_1=1.4+0.3; $T_2 = 6.1 \pm 1,2$ sec; $T_k = 1$ sampling period, sec. The values of the coefficients of the PID controller k_p, k_i, k_d, optimized for the objective function of the mean square error, respectively, amounted to 0.62 kJ/kg; 0.12 kJ sec/kg; 2.14 kJ/kg, according to the objective function of the integral absolute error, amounted to 0.62 kJ/kg; 0.12 kJ sec/kg; 2.14 kJ/kg, according to the objective function of the integral absolute error, respectively – 0.66 kJ/kg; 0.069kJ sec /kg; 1.40 kJ/kg.

From the studies: the PID controller, the regulation time was 0.48 seconds, the maximum value of overshoot was 17.6 percent.

The PID controller with optimization of parameters according to the objective function – the standard error of 0.018 and the objective function - the integral absolute error of 18.65, the control time was 0.7 seconds; the maximum value of the overshoot was 11.2 %.

From the results of studies conducted under conditions of short-term stepwise disturbing influences, it was found that a PID-controller with optimized parameters has a 6.4 % lower overshoot, a 1.45 times shorter setup time for a controlled parameter compared to a PID-controller with non-optimized parameters.

Thus, studies of a digital PID controller with optimized settings showed that such a controller, in comparison with a PID-controller with non-optimized settings, has better dynamic characteristics (less overshoot).

INVESTIGATIONS OF THE COMBINED DIGITAL ACS IN FPGA

The developed scheme of a combined digital ACS based on a P-controller with regulation by the deviation of the controlled variable from its predetermined value, as well as by the perturbation applied to the controlled variable, is implemented in FPGA by designing the device in Quartos II CAD (Fig. 8).

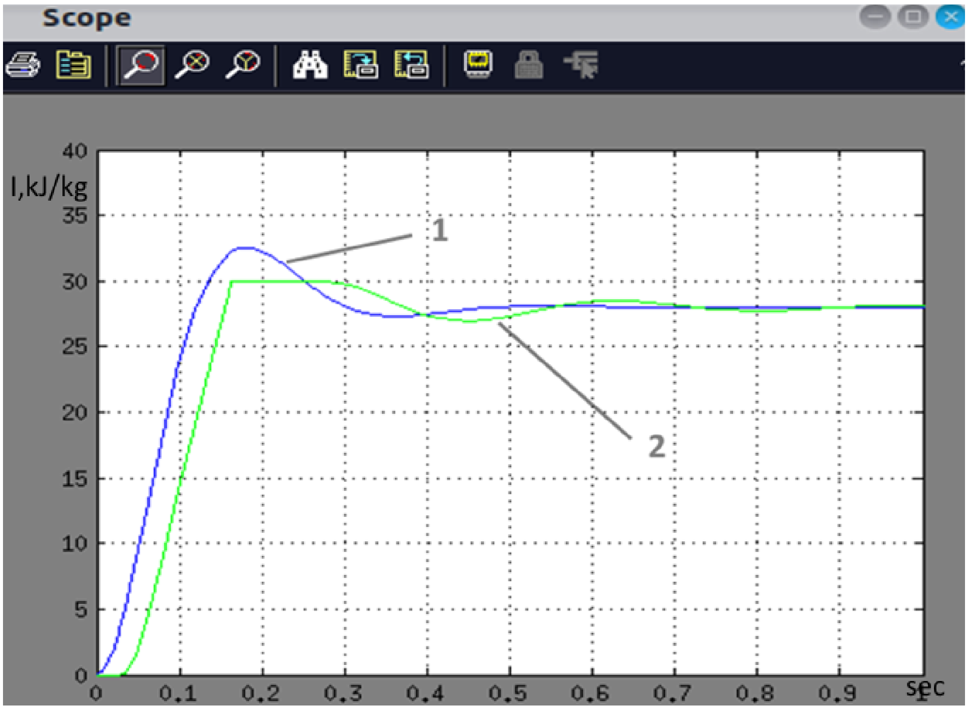

Fig. 7. **Research PID-controller:**
1 – PID-controller; 2 – PID-controller with optimization settings
***Source*: compiled by the author**

The simulation of the studied ACS was carried out in MATLAB-Simulink.

In the simulation, we used the previously obtained data for an air heater of a CACS [31]: transmission coefficients K_1=0.421+0.06; $K_2 = 0{,}813 \pm 0{,}17$ kJ/(kg %); time T_1=1.4+0.3; $T_2 = 6.1 \pm 1{,}2$ sec; gear ratio P -controller $K_p = 98{,}90$; $\rho = 12{,}50$ sec^{-1}; quantization period Tк (delay operator $Z^{-1} = T_k = 1$, sec).

The results of a study of a combined digital ACS based on a P-controller when changing a step perturbing effect on the heat content of air in front of the RO are shown in Fig. 9.

From the studies of a combined ACS with regulation on the deviation of the controlled variable from its predetermined value, as well as on the perturbation applied to the controlled variable it also follows that the steady state is characterized by a zero statistical error.

The regulation time was 2 seconds. The maximum overshoot does not exceed 7 percent.

Studies of the combined ACS with regulation by the deviation of the controlled variable from its predetermined value, as well as by the perturbation applied to the controlled variable, allowed us to establish the following.

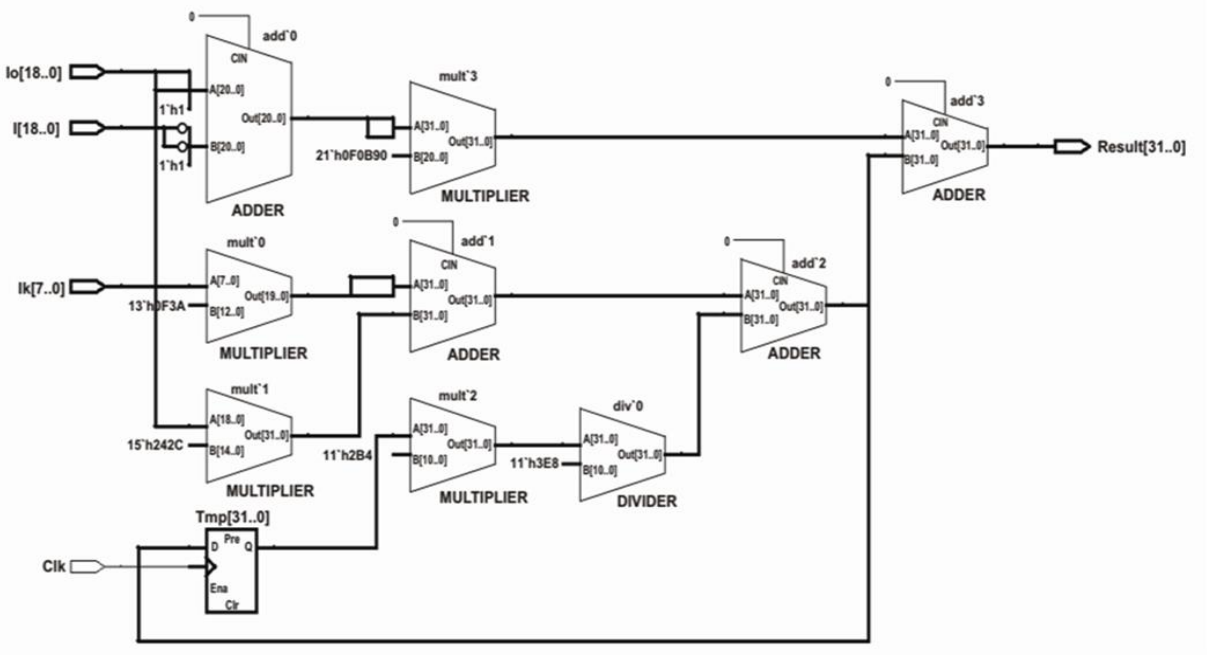

Fig. 8. **Design scheme of a combined ACS for configuration in FPGA**
***Source*: compiled by the author**

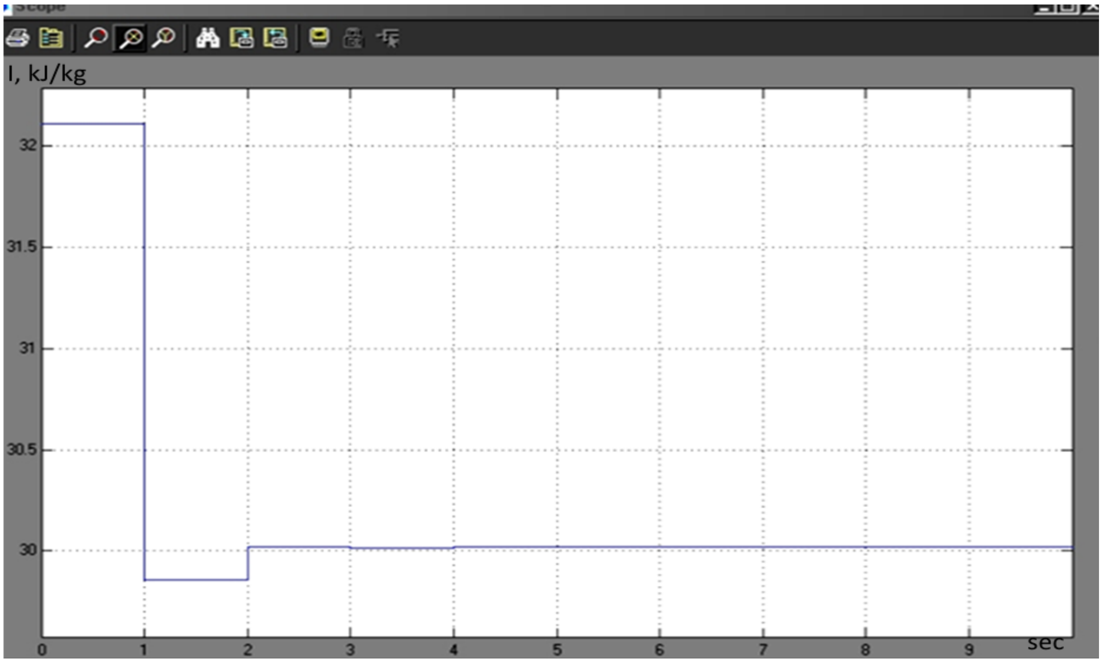

Fig. 9. **The results of the study of combined digital ACS**
***Source*: compiled by the author**

The choice of the quantization period is significantly affected by the dynamics of the RO. For relatively small values of the quantization period $T_{\text{к}}$ equal to 1 sec.

The transition process practically coincides with the processes in a continuous combined ACS. For $T_{\text{к}}$= 3 sec the quality of the transition process can still be considered quite satisfactory, but at $T_{\text{к}}$ greater than 5 sec it becomes unsatisfactory.

Depending on the parameters of the ACS (Table), the time to establish the adjustable coordinate T_u and the magnitude of the control error dI increase with an increase in the quantization period (Fig. 10 and Fig. 11), which means that the quality of regulation deteriorates.

Table. **Combined ACS parameters for different quantization periods**

The parameters of the combined regulator	Tк, sec						
	1	3	5	7	9	11	13
a1	0,4900	0,1170	0,2810	0,0067	0,0016	0,0004	0,0001
a2	0,8490	0,6110	0,4400	0,3260	0,2320	0,1650	0,1180
b1	0,3000	0,3000	0,3000	0,3000	0,3000	0,3000	0,3000
b2	0,1330	0,1330	0,1330	0,1330	0,1330	0,1330	0,1330
A	0,0740	0,0260	0,0157	0,0113	0,0088	0,0072	0,0061
B	0,3600	0,4100	0,4140	0,4160	0,4170	0,4180	0,4190
C	0,9260	0,9740	0,9840	0,9890	0,9910	0,9930	0,9940

***Source*: compiled by the author**

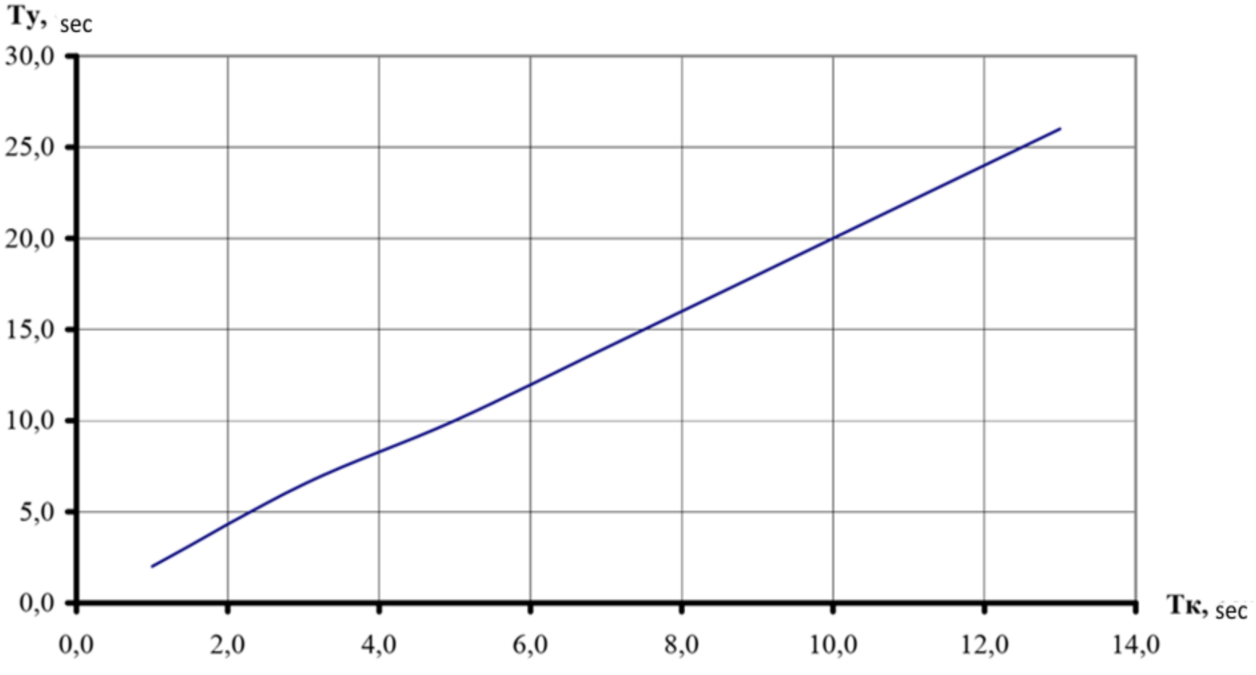

Fig.10. **Dependence of the time it takes to establish an adjustable coordinate on the value of the quantization period**

***Source*: compiled by the author**

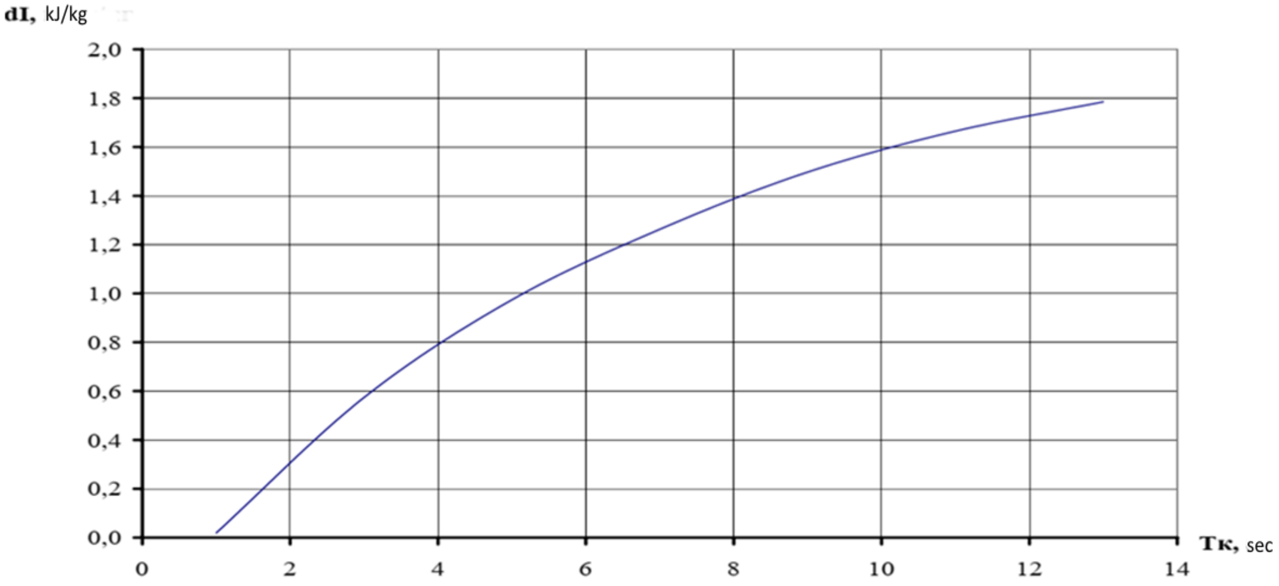

Fig.11. **The dependence of the magnitude of the regulation error on the magnitude of the quantization period**
***Source*: compiled by the author**

COMPARATIVE ANALYSIS OF THE QUALITY OF PID-CONTROLLER REGULATION WITH OPTIMIZATION OF SETTINGS BASED ON DE AND A COMBINED DIGITAL ACS

From the conducted studies of a combined ACS based on a P-controller with regulation by the deviation of the controlled variable from its predetermined value, as well as by the perturbation applied to the controlled variable, it follows that the steady state is characterized by a zero statistical error. The regulation time is 2 seconds. The maximum overshoot does not exceed 7 %. Compared with a PID-controller with optimized parameters, the combined ACS has a 5 % lower overshoot, but a 2.8 times longer setup time for the controlled parameter. For a CACS selected as an air heater, the time constant is tens of seconds. Therefore, the establishment time of the controlled parameter of the PID controller with the optimization of settings based on DE equal to 0.48 sec and the combined digital ACS – 2 sec does not affect the quality of regulation.

However, the magnitude of the maximum overshoot is critical for the heat transfer apparatus OR. Therefore, the developed combined ACS, which has a smaller overshoot in comparison with the PID-controller with optimized parameters, has the advantage.

CONCLUSION

Studies of a digital PID-controller with optimization of settings based on DE and a combined ACS based on a P-controller with regulation by the deviation of the controlled variable from its predetermined value, as well as by the disturbance applied to the controlled variable, made it possible to establish that both controllers operate stably in real-time mode with a minimum amount of regulation and permissible regulation time.

The assessment of the quality of regulation of the combined ACS based on the P-regulator showed that the maximum value of the overshoot does not exceed 7 %. Evaluation of the quality of regulation of the PID-controller with optimization of the parameters according to the objective function made it possible to establish that the maximum overshoot was 11.2 %.

From the results of the studied regulators, it follows that the use of a P-controller with synthesized corrective link provides better indicators of the quality of regulation than in the case of using a PID-controller with optimized parameters for automation of heat exchangers subject to significant disturbances.

The implementation of the developed digital controllers for self-propelled guns with CACS in the FPGA was accompanied by minimal material costs and reduced design time.

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Conflicts of Interest: the authors declare no conflict of interest.

Received 23.05.2019
Received after revision 30.10.2019
Accepted 12.11.2019

DOI: https://doi.org/10.15276/aait.04.2019.7
УДК 62-503.57

НАСТРОЙКА ПАРАМЕТРІВ РЕГУЛЯТОРІВ В ПРОГРАМОВАНОЇ ЛОГІЧНОЇ ІНТЕГРАЛЬНОЇ СХЕМОЮ ДЛЯ СИСТЕМ АВТОМАТИЧНОГО УПРАВЛІННЯ ТЕПЛООБМІННИМИ АПАРАТАМИ

Володимир Вікторович Вичужанін
ORCID: https://orcid.org/0000-0002-6302-1832 vint532@yandex.ua,
Одеський національний політехнічний університет, пр-кт Шевченка,1. Одеса, 65044, Україна

АНОТАЦІЯ

У статті наведено результати синтезу цифрових регуляторів для систем автоматичного управління теплообмінними апаратами центральних систем кондиціонування повітря, що функціонують при змінних істотних обурюють впливах. Розроблені регулятори покликані забезпечити задану якість регулювання (малі час регулювання, допустима величина перегуліровани), зміни параметрів настройки регуляторів з урахуванням умов експлуатації об'єкта регулювання. Схемні рішення регуляторів повинні бути відносно простими. Реалізація вимог до розроблюваних регуляторам здійснена в цифровому типовому ПІД-регуляторі з оптимізацією його параметрів настройки за допомогою алгоритму диференціальної еволюції. Для оцінки якості регулювання ПІД-регулятор тестувався в програмі ModelSim. Результати тесту аналізувалися за допомогою Matlab. З метою реалізації вимог до розроблюваних регуляторам в якості альтернативи ПІД-регулятора з оптимізацією його параметрів настройки за допомогою алгоритму диференціальної еволюції створена комбінована автоматична система регулювання на основі П-регулятора. Система регулювання містить П-регулятор з синтезованим коригуючих ланкою, що забезпечує регулювання по відхиленню регульованої змінної від заданого її значення і по обуренню, прикладеного до регульованої змінної. Оцінка якості регулювання П-регулятора з коригувальним ланкою здійснена за результатами досліджень в Matlab. ПІД-регулятор з оптимізацією його параметрів настройки за допомогою алгоритму диференціальної еволюції, а також П-регулятор з коригувальним ланкою реалізовані в ПЛІС. Основною мовою опису апаратного забезпечення реалізації регуляторів в ПЛІС вибрана мова для високошвидкісних інтегральних схем (VHDL). Порівняльний аналіз результатів дослідження цифрового ПІД-регулятора з оптимізацією параметрів і комбінованої АСР дозволили встановити, що регулятори задовольняють необхідній якості регулювання при автоматизації теплообмінних апаратів центральних систем кондиціонування повітря, що піддаються впливу істотних збурень. Вони мають можливість зміни параметрів настройки з урахуванням умов експлуатації об'єкта регулювання. Було встановлено, що використання П-регулятора з синтезованим коригуючих ланкою, що володіє більш простим схемним рішенням, дозволяє забезпечити кращі показники якості регулювання в порівнянні з ПІД-регулятором з оптимізованими параметрами налаштування.

Ключові слова: цифровий ПІД-регулятор; диференціальна еволюція; комбінована автоматична система регулювання; програмована логічна інтегральна схема; теплообмінний апарат

DOI: https://doi.org/10.15276/aait.04.2019.7
УДК 62-503.57

НАСТРОЙКА ПАРАМЕТРОВ РЕГУЛЯТОРОВ В ПРОГРАММИРУЕМОЙ ЛОГИЧЕСКОЙ ИНТЕГРАЛЬНОЙ СХЕМЕ ДЛЯ СИСТЕМ АВТОМАТИЧЕСКОГО УПРАВЛЕНИЯ ТЕПЛООБМЕННЫМИ АППАРАТАМИ

Владимир Викторович Вычужанин
ORCID: https://orcid.org/0000-0002-6302-1832, vint532@yandex.ua, Scopus ID: 57193025809
Одесский национальный политехнический университет, проспект Шевченко, 1. Одесса, 65044,Украина

АННОТАЦИЯ

В статье приведены результаты синтеза цифровых регуляторов для систем автоматического управления теплообменными аппаратами центральных систем кондиционирования воздуха, функционирующих при переменных существенных возмущающих воздействиях. Разработанные регуляторы призваны обеспечить заданное качество регулирования (малые время регулирования, допустимая величина перегулирования), изменения параметров настройки регуляторов с учетом условий эксплуатации объекта регулирования. Схемные решения регуляторов должны быть относительно простыми. Реализация требований к разрабатываемым регуляторам осуществлена в цифровом типовом ПИД-регуляторе с оптимизацией его параметров настройки с помощью алгоритма дифференциальной эволюции. Для оценки качества регулирования ПИД-регулятор тестировался в программе ModelSim. Результаты теста анализировались с помощью Matlab. В целях реализации требований к разрабатываемым регуляторам в качестве альтернативы ПИД-регулятору с оптимизацией его параметров настройки с помощью алгоритма дифференциальной эволюции создана комбинированная автоматическая система регулирования на основе П-регулятора. Система регулирования содержит П-регулятор с синтезированным корректирующим звеном, обеспечивающим регулирование по отклонению регулируемой переменной от заданного ее значения и по возмущению, приложенного к регулируемой переменной. Оценка качества регулирования П-регулятора с корректирующим звеном осуществлена по результатам исследований в Matlab. ПИД-регулятор с оптимизацией его параметров настройки с помощью алгоритма дифференциальной эволюции, а также П-регулятор с корректирующим звеном реализованы в ПЛИС. Основным языком описания аппаратного обеспечения реализации регуляторов в ПЛИС выбран язык для высокоскоростных интегральных схем (VHDL). Сравнительный анализ результатов исследования цифрового ПИД-регулятора с оптимизацией параметров и комбинированной АСР позволили установить, что регуляторы удовлетворяют требуемому качеству регулирования при автоматизации теплообменных аппаратов центральных систем кондиционирования воздуха, подверженных воздействию существенных возмущений. Они обладают возможностью изменения параметров настройки с учетом условий эксплуатации объекта регулирования. Было установлено, что использование П-регулятора с синтезированным корректирующим звеном, обладающим более простым схемным решением, позволяет обеспечить лучшие показатели качества регулирования в сравнении с ПИД – регулятором с оптимизированными параметрами настройки.

Ключевые слова: цифровой ПИД-регулятор; дифференциальная эволюция; комбинированная автоматическая система регулирования; программируемая логическая интегральная схема; теплообменный аппарат

ABOUT THE AUTHOR

Vladimir V. Vychuzhanin, Dr. Sci. (Eng), Professor, Head of the Department Information Technology Department, Odessa National Polytechnic University, 1, Shevchenko Avenue. Odesa, 65044, Ukraine
vint532@yandex.ua, ORCID: http://orcid.org/0000-0002-6302-1832

Research field: Information and Technology Support of Functional and Topological Structures of Distributed Systems

Володимир Вікторович Вичужанін, д-р техніч. наук, проф., зав. каф. Інформаційних технологій. Одеський національний політехнічний університет, пр-т Шевченка,1. Одеса, 65044, Україна