DEVELOPMENT OF AN AUTOMATION PROGRAM AND PID CONTROLLER COEFFICIENTS TESTING FOR OPTIMAL CONTROLLING THE AIR HEATING/COOLING PROCESS IN MOBILE COMPLEXES

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ABSTRACT

The article discusses the problems and features of the air conditioning systems implementation for mobile complexes in Kazakhstan. The method of conducting an experimental study for selecting the optimal coefficients of the PID controller are presented. The selection of equipment for the experiment is carried out, taking into account the features of the air conditioning systems use in the sharply continental climate of Kazakhstan. The algorithm of automation operation is also given, according to which a program will be created to control the process of heating/cooling air in the mobile complex. The connection diagram of the devices that will be used during the experiment is described. The general principle of PID controller's operation is considered. At the next stage, the coefficients of the PID controller found by the methods of the amplitude optimum, Ziegler-Nichols and Stogestad are calculated and taken from the sources. According to the developed algorithm, in the OwenLogic application created a program. At the final stage of the experiment, the coefficients found by different methods are set in the PID controller and the output power characteristics are removed. Later, they are compared. On the theoretical knowledge basis, the best characteristic is selected, which will be optimal for use in the air heating/cooling processes in the mobile complexes on the Kazakhstan state.

Keywords: *Mobile Complexes, Automation Of Air Conditioning Systems, PID Controller, PID Controller Coefficients, Automation Algorithm*

1. INTRODUCTION

Mobile complexes represent universal solutions for performing a whole range of tasks, such as deploying mobile command headquarters, communication centers, emergency response centers, operating rooms and other [1]. In such complexes increased demands are applied to air conditioning systems, they are primarily associated with work in the difficult climatic conditions of Kazakhstan, with temperatures from -40 to +50 ° C [2]. They must be designed for a large cooling capacity, because shelters are made from painted aluminium panels and have the ability to transfer a large amount of heat emanating from sunlight, on average up to 170 W/m^2 °C, which significantly increases heat gain, in accordance with formula [3]:

$$Q_S = F_S \cdot k \cdot (t_{AT} - t_{IN}) \tag{1}$$

where F_S – heat-transfer surface area, m2; k – heat transfer coefficient; t_{AT} – heated surface average temperature, °C; t_{IN} – rooms air temperature, °C.

Based on the author's personal experience in the development of mobile complexes, air conditioning systems in such complexes are aimed only at cooling the air mass, because usually in wintertime air heaters running on diesel are using

[4]. Nevertheless, based on the experience of using mobile complexes by special forces, it can be concluded that in winter the complexes are often kept in unheated boxes, and diesel fuel does that are using, not always meet the standards for wintertime. This, in turn, leads to the impossibility of starting a diesel generator and, accordingly, air heaters (here it is necessary to make a note that, as a rule, air heaters use diesel fuel from the generator tank) due to freezing of diesel fuel in the fuel lines of the heaters (sometimes this is due to the small diameter of the fuel line). Based on the above, it can be concluded that an electric heater must be built into air conditioning system [5, 6], which will allow heating the interior of the complex using electricity (here it is necessary to make a note that if it is impossible to start a diesel generator, mobile complexes are connected to the industrial power grid). In addition, a separate factor is that the shelters of mobile complexes have a sealed design [7] to prevent the ingress of external air into the internal space, because this air can be contaminated chemical or radio harmful substances. Based on this, the air conditioning system should not have an inflow of fresh, untreated air. For air inflow into the complex, as a rule, special filter-ventilation units are used, which are able to provide purified from pollution air inflow [8].

In the mobile complexes air conditioning systems developing process, one of the most important factor is power grid total load reducing, since the power supply systems of such complexes are often not very powerful, author's personal experience based, the power is about 15 kW. In air conditioners of mobile complexes, it is advisable to use systems with adjustable performance, that are maintained at the required level by changing the compressor engine speed. This method also saves current when starting a high-capacity load such a compressor. Mobile complexes power supply circuits are very sensitive to high inrush currents, since their performance designed for the minimum load at startup. In the event when inductive load, such as a compressor, is turned on at maximum power, it will be necessary to select power circuits with a 20-30% margin, which will entail additional costs during production [9]. Accordingly, to ensure a smooth and relatively long process of increasing the compressor output power to 100%, it is necessary to use PID controllers [10, 11]. At the same time, the task facing the PID controller in the mobile complex will be the smooth start of the compressor, heating elements and fans to ensure the lowest possible load on these components, as well as the power grid.

The main result of the work should be the solution of the listed problems for the implementation air heating/cooling process control system in the mobile complex:

1) selection of a controller and a temperature sensor for the air conditioning system of a mobile complex, based on the need for their functioning in a given temperature range;

2) creating a program to control the process of heating and cooling air, based on the described requirements;

3) PID controller coefficients selection and testing to ensure maximum reliability of the automation system and the air conditioning system as a whole.

The literature sources that are given in the article were selected on the following principles basis:

1. Applicability to this work.
2. Scientific novelty.
3. Theoretical significance.
4. Practical significance.
5. Originality of knowledge.

2. METHODIC AND PROCESS OF EXPERIMENT

The experiment method will include five consecutive stages:

1. Automation equipment selection for the experiment.
2. Program development in accordance with the algorithm in Figure 1.
3. Substitution of PID controller coefficients that are taken from the literature.
4. Capture the results using an oscilloscope.
5. PID regulation obtained results comparison.

To solve the first problem posed in the introduction, an analytical method is suitable, which will allow you to choose the necessary controller and sensor from the existing on the automation market. For research and development automated air condition system circuit, the programmable relay 102-24.2416.06.1 of the OWEN company will be used [12]. According to the manufacturer, the relay can be used to control ventilation, pumps and other devices. Table 1 shows the technical characteristics of the device in the presented modification.

As can be seen from table 1, one of the important characteristics is a rather wide temperature range, which will allow the relay to start and measure the current temperature outside the

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complex, and, on it basis, draw conclusions about the further operation mode. The device is also equipped with a large number of discrete and analog inputs/outputs, which will allow implementing protection and control circuits for the entire air conditioning system of the mobile complex.

Table 1: Technical characteristics of programmable relay 102-24.2416.06.1

Name	Value
General specifications	
Programming environment	OwenLogic
Retain memory capacity	1016 bytes
Stack	Dynamic
ROM memory	128 kB
RAM memory	32 kB
Programming interface	USB
Supply voltage	24 V
Operating temperature	from -40 to +55
Discrete inputs	
Quantity	16
Nominal supply voltage	24 V
Galvanic isolation	Group, 4 inputs each
Analog inputs	
Quantity	8
Type of measured signals	0 ... 10 V 4 ... 20 mA 0 ... 300 kOhm
Limit of basic reduced error	± 0.5%
Four channels measurement results updating period	20 ms
Discrete operation	Yes
Discrete outputs	
Quantity	14
Type	Relay (normally open)
Permissible load current, no more than	3 A on voltage no more than 30 V DC
Galvanic isolation	Individual
Analog outputs	
Quantity	2
Output signal type	0 ... 10 V 4 ... 20 mA

The temperature and humidity sensor 100-H4.2.И.2 of the OWEN company will act as a temperature sensor [13]. This industrial sensor is designed to continuously convert relative temperature and humidity into two unified 4 ... 20 mA signals. Detailed characteristics of the sensor in table 2 are given.

Table 2: Technical characteristics of temperature and humidity sensor 100-H4.2.И.2

Name	Value
Relative humidity measurement range	0…100 %RH
Ambient air temperature measurement range	-40…+80 °C
Protection class	IP65
Output signals	two channels 4…20 mA

Relay will be programmed in the OwenLogic application, which nave user-friendly graphical interface and a wide range of functions. The program will be written according to the operation algorithm shown in Figure 2 [14, 15, 16, 17].

To solve the second and third tasks, a practical method is suitable, with the help of which air conditioning system operation program will be developed, and on its basis, the optimal coefficients of the PID controller will be selected [18].

The temperature sensor will be connected to the programmable relay. The relay will be powered from a 24 VDC power supply. An Agilent oscilloscope will have connected to the analog output of the controller for characterization and tuning PID controller. In general, the layout of the test bench shown in Figure 1.

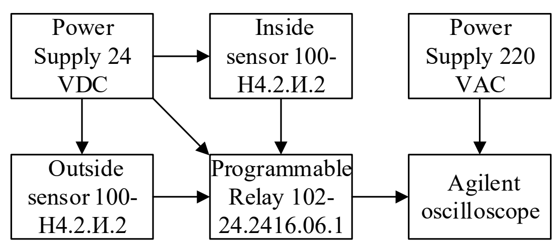

Figure 1: PID controller coefficients tuning stand

PID controllers are universal in terms of their configuration capabilities, and you can use them to get any regulation law. PID controllers affect the controlled parameter in proportion to the deviation ε of the controlled value, the integral of this deviation, and the rate of controlled value change:

$$\mu = k_p \cdot \varepsilon + \frac{1}{T_i}\int_0^t \varepsilon dt + T_d \frac{d\varepsilon}{dt} \qquad (2)$$

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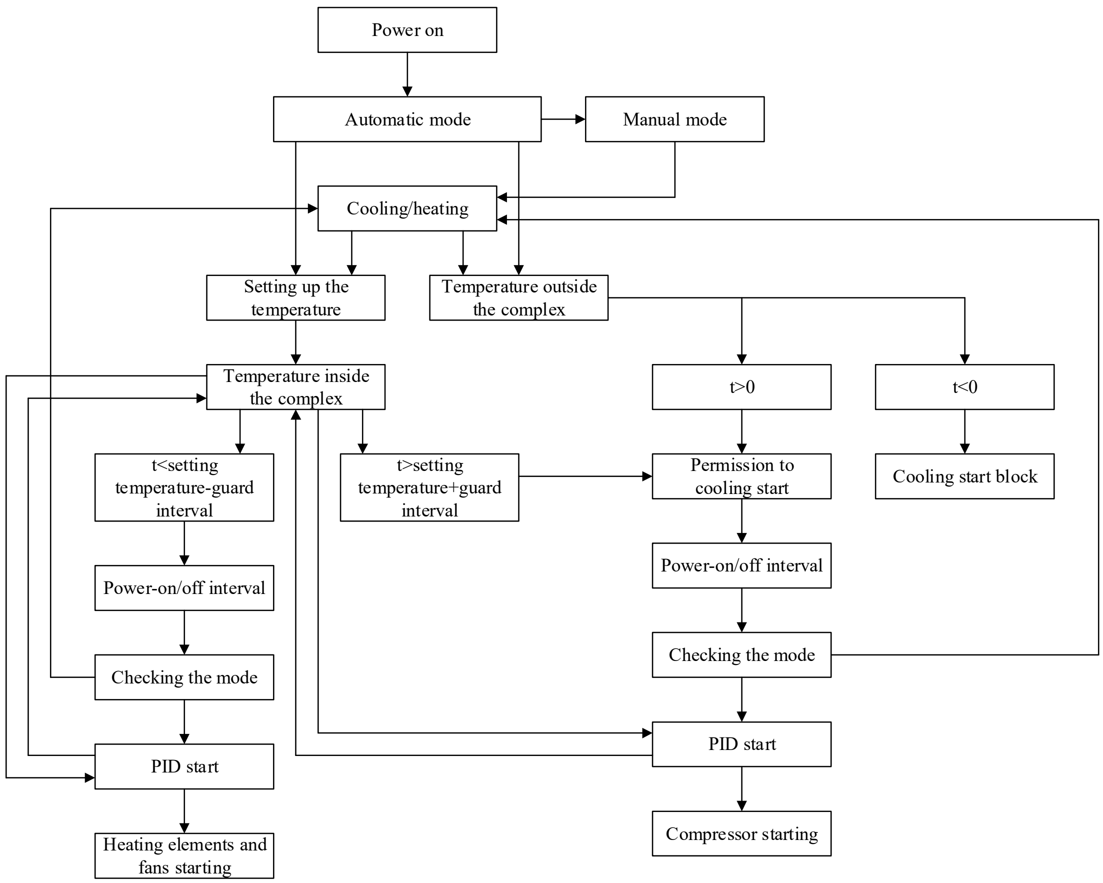

Figure 2: Automation system algorithm

The block diagram of the PID controller are shown in Figure 3.

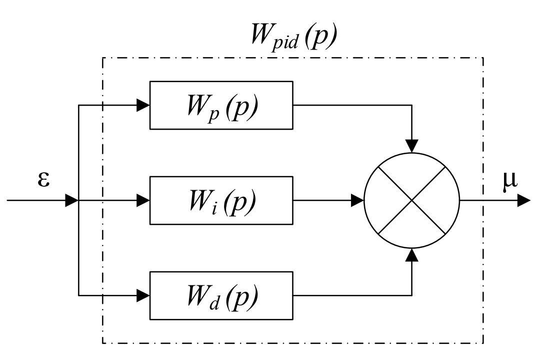

Figure 3: PID controller structural diagram

The law of an ideal PID controller regulation when a constant signal $\varepsilon(t)=\varepsilon_0$ is received at the input of the controller is shown in figure 4. In a standard PID controller, there are three components and each of them affects the control in its own way. Proportional takes into account the amount of mismatch between the set value and the actual value, integral component is used to eliminate the static error, differential considers the rate of change of controlled variable, counteracting the alleged deviations caused by disturbances of the system or lag.

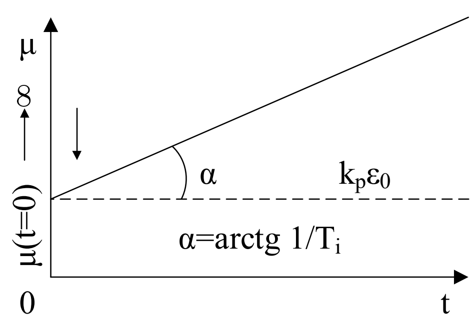

Figure 4: The law of PID control

Today, there are few methods of PID controllers tuning, which is include the following methods: amplitude optimum, Stogestad, Kuhn, Schedel and many other methods [19]. Each of the methods offers a specific practical or theoretical approach to solving the problem of PID controller coefficients finding. For optimal PID controller tuning, consider some of them.

The amplitude optimum method consists in maintaining closed control loop transfer function value at the level of unity for the control action [19]. In this case, the transfer function of the regulator will be as follows:

$$w(s) = k_p + \frac{k_i}{s} + k_d s \quad (3)$$

where k_i, k_d, k_p – are PID controllers integral, differential and proportional coefficients.

The coefficients can found by calculating the matrix:

$$\begin{bmatrix} k_p \\ k_i \\ k_d \end{bmatrix} = \begin{bmatrix} -A_1 & A_0 & 0 \\ -A_3 & -A_2 & -A_1 \\ -A_5 & A_4 & -A_3 \end{bmatrix}^{-1} \begin{bmatrix} -0{,}5 \\ 0 \\ 0 \end{bmatrix} \quad (4)$$

This method requires calculations, source [19] contains the results that was founded by this method: $k_i = 6.757$; $k_d = 9.749$; $k_p = 16.662$. Next, it is need to consider the remaining options and choose the most suitable one.

Ziegler-Nichols method is experimental, and for its implementation, it is necessary to set the differential and integral coefficients to zero, i.e. activate the regulator only in the P-regulation mode, increasing the proportional component until appear oscillations in the system, which have the form shown in Figure 5. Then it is necessary to measure the oscillation period and set the regulator parameters in accordance with the formulas presented in table 3. The Ziegler-Nichols method is one of the simplest methods for setting up PID controllers, but this method is still used today. It allows to find the necessary coefficients of the PID controller without using complex mathematical calculations.

The parameters given in Table 3 in different sources have different values [19, 20] Therefore, for convenience, the values are taken from two sources.

Table 3: PID controller parameters

Source	k_p	k_i	k_d
[19]	0,60 k_p	1,2 k_p/T	0,75 k_p/T
[20]	0,60 k_p	2 k_p/T	k_p $T/8$

As a result of setting up the system, Table 3 values based, the coefficients shown in Table 4 were obtained.

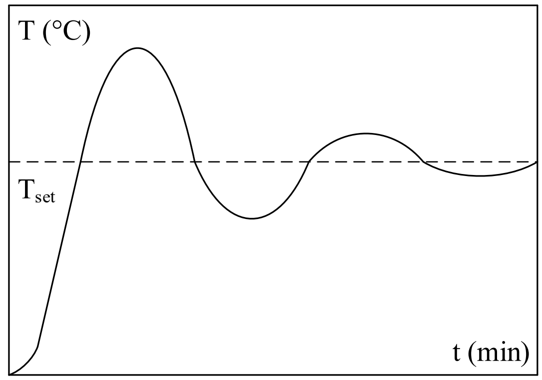

Figure 5: Oscillations when tuning the PID controller by the Ziegler-Nichols method

Also, one of the methods for selecting the coefficients of the PID controller is the Stogestad method, which consists in identifying the control object model parameters, and further determining the necessary PID controller tuning coefficients [19]. For a second-order aperiodic link with a transport delay, the parameters can be found by the formula:

$$k_p = \frac{T_1}{k(T_c + \tau)}, \quad T_i = min[T_1; c(T_c + \tau)], T_d = T_2 \quad (5)$$

where T_1, T_2, k, τ – object parameters; c – parameter providing an aperiodic form of the transient process at the output of the control system. In the source [19], according to this method, the following parameters were obtained: $k_i = 12.9$; $k_d = 9.6$; $k_p = 10.3$.

Table 4: PID controller founded parameters

Method	k_p	k_i	k_d
Amplitude optimum	16,662	6,757	9,749
Ziegler-Nichols 1	0,06	0,192	0,12
Ziegler-Nichols 2	0,06	0,32	0,78
Stogestad	10,3	12,9	9,6

3. SIMULATION RESULTS AND THEIR DISCUSSION

The controller operation program is shown in Figure 6. In this circuit, the on/off signal is a discrete 24 V voltage signal that appears when voltage is applied to the complex from a diesel generator or from an external source. T_{out} is a 4 ... 20

mA signal coming from the 100-H4.2.И.2 temperature sensor, which is located outside the complex. T_{in} – 4 ... 20 mA signal coming from the 100-H4.2.И.2 temperature sensor, which is located inside the complex. T_{cust} is a signal set by the user of the air conditioning system (setting the required temperature), range of his possible values are from 16 to 30 degrees. Cool and heat signals are signals when heating or cooling is manually activated. Signal + is a signal stored in the non-volatile memory of the controller, it is a guard interval to prevent multiple cycles turning on and off of heating and cooling modes. Signal 0 prevents the air conditioner from starting in cooling mode when the outside temperature is less than 0 degrees Celsius, this signal prevents components damaging. A value of 100 is used to divide the power output of the PID controllers and adapt it to the analog outputs.

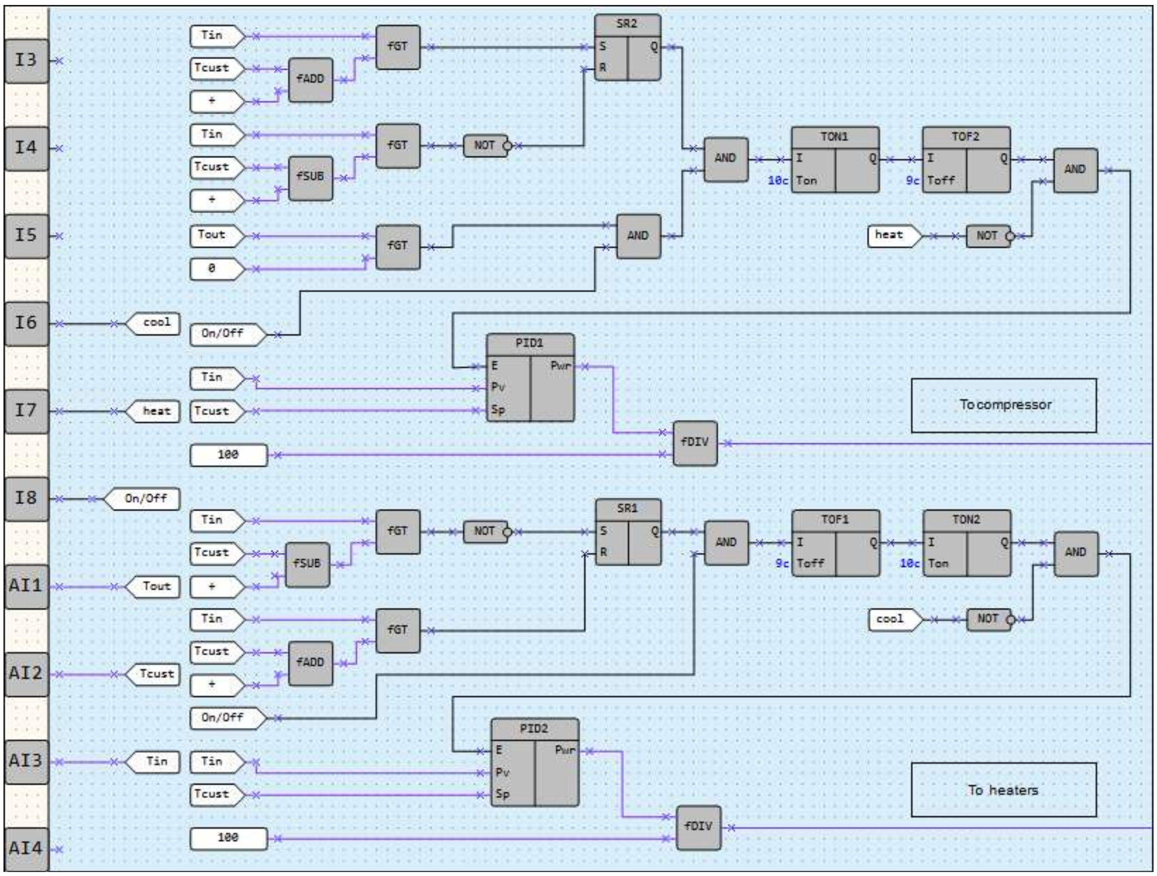

Figure 6: Program for air conditioner

When automatic mode is operating, after power is supplied in the complex, it becomes possible to start heating and cooling systems. User sets the required temperature in the complex, or uses the last one settings. fADD blocks add the guard interval value to sets by users temperature. fSUB blocks subtract the value of the guard interval from the set temperature. In four cases, the fGT blocks compare the values obtained from the fADD / fSUB blocks with the current temperature in the complex's inner space. One of the fGT blocks compares the temperature outside the complex with a zero value. If the temperature outside the complex is higher than 0 degrees Celsius, the fGT block gives the resulting logical "1" and allows the cooling system to start. If the temperature is below 0, fGT gives a logical "0" signal and thereby blocks the activation of the cooling mode. Logic "NOT" inverts the signals from the fGT blocks and thus creates a comparison to a lower value. Then, SR flip-flops with turn-on priority give logical signals. If the temperature in the complex is higher than the set value, the SR2 trigger enables the cooling system to work. If the temperature is below the user-specified value, trigger SR1 enables the heater to operate. If the temperature inside the complex goes above or below the value set by the user when system is operating, the SR triggers receive signals to turn off/on the heating/cooling modes. Logic "AND", located after the SR flip-flops, compare all information on their inputs and give a further answer about the start of the cooling or heating mode. Timers with delayed on TON and timers with delayed off TOF prevent simultaneous starting of heating and cooling modes in case of a sharp temperature transition in the complex and its passage through the protective intervals. The TOF1 block value should be set slightly less than that of the TON1 block. After the on and off delay blocks, there are logical "ANDs", which, in the case of automatic operation, allow the PID controllers starts. If the user configures the operating mode manually, one of the logical elements "AND" blocks the start of either heating or cooling mode. After the logical "AND" there is a PID controller directly that controls the process of the air heating/cooling, at its inputs there are three signals: a start signal, a signal from the temperature sensor in the complex and a signal set temperature value. Floating point value division units are connected to the PID1 and PID2 outputs, since the output power value on the PID regulators lies in the range from 0 to 100%, and to supply it to the analog output for controlling the compressor, heating element and fans, it must be reduced to acceptable values. PID1 works in cooling mode, PID2 in heating mode.

It is worth noting that the algorithm shown in figure 4 is intended for use in single-zone air conditioners with inverter control. Inverter control has the following advantages:

- compressor on/off cycles are excluded during performance adjustment;
- the range of cooling capacity of one air conditioner changes;
- starting currents are reduced to values less than operating;
- compressor mechanical parts wear reduced;
- increases the reliability and service life of the air conditioner;
- increases the accuracy of maintaining the temperature;
- provides quick access to the set temperature mode;
- improves the air conditioner control and protection system quality [21, 22, 23].

The developed circuit has been tested under various possible conditions. Was carried practical analysis out for the presence of contradictions and errors in the operation of the system, during this analysis they were not identified, therefore, the scheme can be applied in practice [24, 25, 26, 27].

The next stage of work is testing PID controller's coefficients, program shown in Figure 6 based. During this stage, the values of the coefficients were set in the PID controller, obtained in various ways and for convenience summarized in Table 4.

In the course of the study, it is planned to determine the performance of the PID controller when setting various coefficients. It is also necessary to choose the best method for finding parameters, taking into account objective requirements for the quality of regulation.

The inside temperature was maintained at 45 Celsius degrees, the required temperature setpoint was at 23 degrees. When setting the coefficients obtained by the amplitude optimum method, the picture shown in Figure 7 was observed. Power increased from 0 to 100% in 0.5 sec. and it became quite obvious that this result is not suitable, because it is necessary to smoothly increase the power over a rather long period. To save the amplitude optimum method, it was decided to reduce the coefficients by 10 times and repeat the experiment, since based on the resulting graph, the coefficients are too high. After reducing the coefficients, the picture presented in Figure 8 was observed, this result is quite acceptable, but nevertheless, the increase in power occurs too quickly. To increase the process time, the integral coefficient was increased to a value of 2, and the increase in power occurred smoothly within 1 minute. This result is quite acceptable, since further increase in the integral component can increase the duration of the process to the required level.

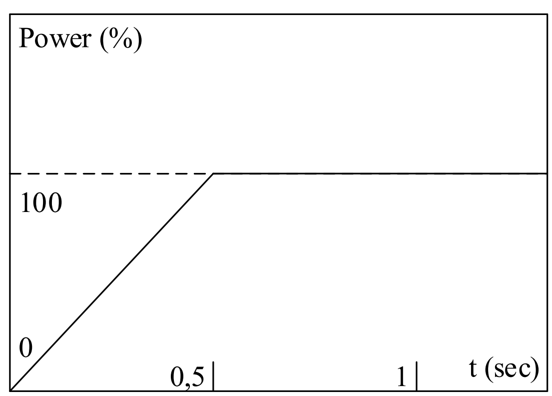

Figure 7: Graphs of PID controller output power increasing when setting the coefficients obtained by the amplitude optimum method

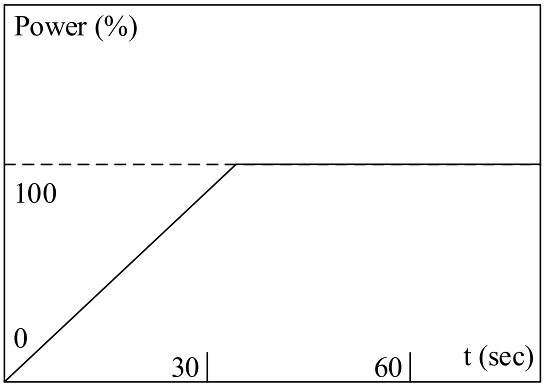

Figure 8: Graph of PID controller output power increasing when setting the amplitude optimum method coefficients reduced 10 times

The next step was to set the coefficients obtained by the Ziegler-Nichols methods 1 and 2, respectively. The result is shown in Figure 9 and 10. Both the first and second Ziegler-Nichols methods showed excellent results, the output power of the PID controller was gradually increased for the first method within 28 seconds, for the second within 36 seconds. With an increase in the integral coefficient to 2, both in the first and in the second case, it was possible to achieve the result of increasing the power from 0 to 100% within 2 minutes 15 seconds, which is acceptable.

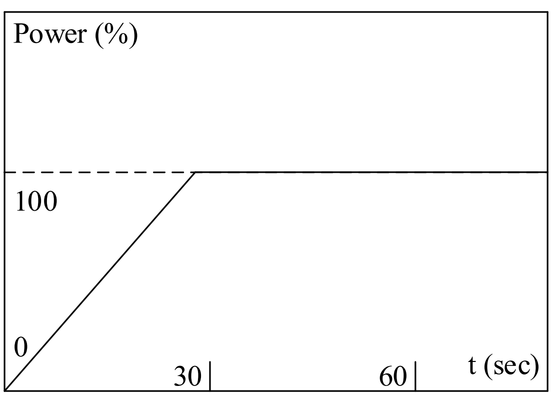

Figure 9: Graph of PID controller output power increasing when setting the coefficients obtained by the Ziegler-Nichols 1 method

It is worth noting that the PID controller coefficients that was found by the Ziegler-Nichols methods 1 and 2 did not require reduction. Also, finding them was not time-consuming or difficult in terms of operations performed.

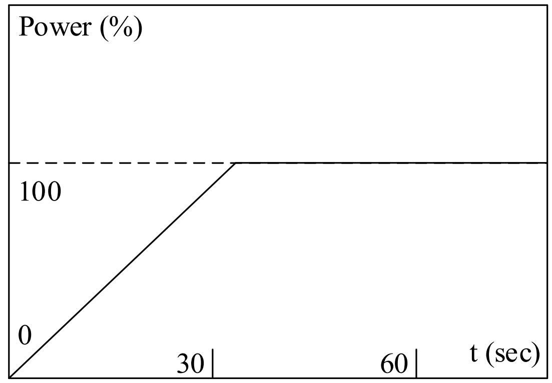

Figure 10: Graph of PID controller output power increasing when setting the coefficients obtained by the Ziegler-Nichols 2 method

The final stage of the experiment was the installation of the coefficients obtained by the Stogestad method, and based on the amplitude optimum results, the coefficients were previously reduced by 10 times. The result of the experiment is shown in Figure 11. When using the coefficients obtained by the Stogestad method, the power gradually increased from 0 to 100% for 22 seconds, to increase the process duration, the integral coefficient was increased to 2 and as a result of this increase, 1 minute and 25 seconds result was obtained, which, as in previous experiments, is acceptable.

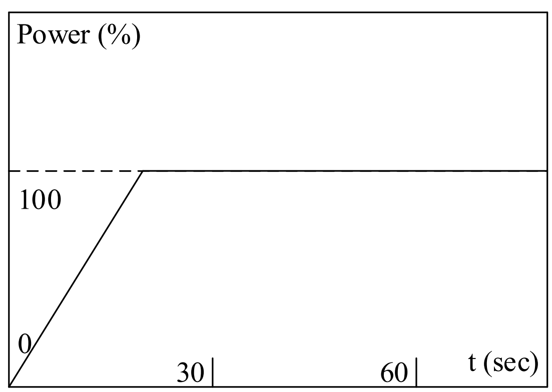

Figure 11: Graph of PID controller output power increasing when setting the coefficients obtained by the Stogestad method

For convenience, the experimental results were listed in Table 5. This table shows that in all four cases, the time results have little difference. However, for the developed air conditioning system,

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the best result will be the one with the longest time to reach the peak output power.

Table 5: Results of experiments

Method	t (sec) with initial parameters	t (sec) with k_i=2
Amplitude optimum (/ 10)	36	60
Ziegler-Nichols 1	28	135
Ziegler-Nichols 2	36	135
Stogestad (/ 10)	22	85

4. CONCLUSIONS

Experiments results carried out in the article affect only the air conditioning systems of mobile complexes (since they require a very smooth start-up to reduce the overall load on the power grid), for other air conditioning systems, the results may be different. For example, in [19], the best method for finding PID controller coefficients is the method of the amplitude optimum. In the source [20], the auto-tuning of coefficients is considered the most optimal.

Mobile complexes are an important element when performing tasks by various services. Air conditioning systems in these complexes are an integral part of the overall life support system. In the production of mobile complexes in Kazakhstan, as a rule, serial air conditioners are used, which do not fully meet the field conditions. For the period from 2017 to 2020, serial air conditioners were used in all mobile complexes developed by the author. Also, the development of mobile systems it is necessary to save the free space inside the shelter, which greatly limited. All these factors require the development of a special air conditioning system designed for specific tasks. The use of inverter control can partially solve the tasks set. The proposed algorithm of the air conditioner operation allows you to maximize all the advantages of using an inverter.

The developed scheme is the optimal solution for cooling and heating air mass inside the mobile complex and allows, in the shortest possible time, to provide the personnel with a room for comfortable work. Also, due to the use of PID controllers, the algorithm allows to reduce the overall load on the power grid and thereby save the power of the diesel generator. This approach avoids wear and tear on the components of the air conditioning system and ensures longer operation, which affects the overall reliability of the system. This factor is decisive, since the failure of such important component as the air conditioning system in the field can disrupt the work, and it will be possible to carry out current repairs only upon mobile complex arrival to the place of permanent deployment. It is worth noting that in the process of further air conditioning system development for the mobile complex, the algorithm of operation can be supplemented. Later in algorithm will be added protection mechanisms.

The research PID controller coefficients, given in the article, is the final stage in solving the problem of air conditioning in mobile complexes. All 4 methods studied in the article have shown their consistency and good results. In all four cases, increasing the integration coefficient led to an increase in the duration of the power increase process, and, as a consequence, to an increase in the system reliability. Finded by different methods PID controller coefficients are shown in Figure 12.

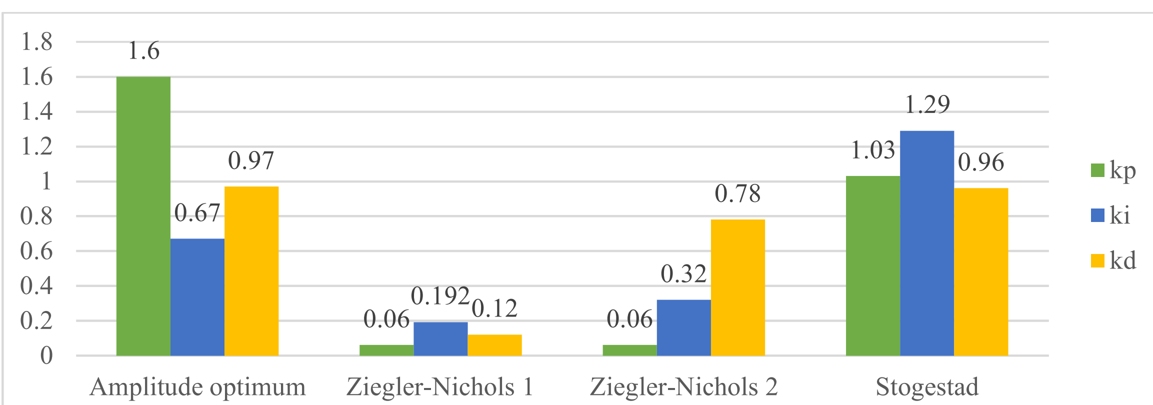

Figure 12: PID controller coefficients finded by different methods

When formulating criteria for setting the PID controller, it is necessary to take into account the response not only to changes in the setpoint, but also to external disturbances. The choice of quality control criteria should be based on the meaning of the problem being solved. In the General theory of automatic control, the structure of the controller is selected based on the model of the control object. However, more complex controls correspond to more complex controls.

To assess the quality of regulation in a closed system with a PID controller, a step input action and a number of criteria for describing the form of the transition process are usually used:

- maximum control error:

$$e_{max} \max_{0<t\infty} |e(t)| \tag{6}$$

and the time T_{max} at which the error reaches this maximum;

- integrated absolute error:

$$e_{IAE} = \int_0^\infty |e(t)|dt \tag{7}$$

- integral of the error square:

$$e_{IAE} = \int_0^\infty e(t)^2 dt \tag{8}$$

- decrement of attenuation d (this is the ratio of the first maximum to the second, the typical value of d=4 or more):

$$d = \frac{a}{b} \tag{9}$$

Nevertheless, if we refer to the general rules given in [28, 29, 30, 31] and obtained by carrying out a large number of theoretical analysis and numerical experiments, the best method is the Ziegler-Nichols 2 method (applicable to air conditioning systems of mobile complexes), since it has the lowest value of the proportional coefficient and the highest value of the differential coefficient, and, consequently, the reliability of the entire system will be significantly higher than that of other methods [32, 33].

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