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DEVELOPMENT OF THE METHOD OF CONSTRUCTING THE EXPANDER TURBINE ROTATION SPEED REGULATOR

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The study is devoted to the expander turbine rotation speed regulator, considering the possibility of implementing this regulator on microprocessor automation tools. The use of expander-generator units in general improves energy saving indicators, and the ability to maintain the turbine shaft rotation speed within the specified limits, in turn, directly affects the indicators of the quality of the generated electricity. The expander turbine, as a control object, is described by non-linear equations, which determines the possibility of using regulators of different designs, and requires the selection of the most suitable one according to certain criteria. As part of the study, based on the tasks of practical implementation of the regulator on microprocessor devices, the expediency of reducing the transfer function of the model in the process of identifying the control object was confirmed. As a result of research on an experimental setup, it is shown that the use of a three-position relay regulator allows for regulation dynamics at the level of a classic PID regulator. An important result of the research is the stabilization of the turbine rotation speed, which affects the parameters of the electricity generated by the generator. The description of the control object was linearized by constructing a family of transfer functions for the operating points of the control range. For the construction of the turbine rotation speed regulator, the criterion of "minimum fluctuation of the parameter when changing its set value" is proposed. A regulator for a non-linear object with oscillatory features is built, which has a simple implementation and a cycle time of 1 ms. It makes it possible to reduce rotation speed fluctuations to 5 % and minimize the impact of rotation process disturbances

Keywords: nonlinear plant, adaptive control, relay regulator, plant model, reduced model

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1. Introduction

One of the ways to increase energy saving indicators in the transportation of natural gas is the use of expander-generator units (EGU). Electricity generated due to the use of excess gas pressure can be consumed both autonomously and by the network of users. In any case, the quality indicators of the generated electricity depend on the stability of the expander turbine, which rotates under conditions of changing gas flow parameters.

Solving the tasks of controlling turbine rotation modes is relevant for the small power industry – mini hydroelectric power plants (HPP) and wind energy devices. The need for control is due to the arbitrary nature of flow disturbances interacting with the turbine blades. Each of the streams has its own flow characteristics, which are considered when developing models and regulators of the control object.

Features of the description of such control objects consist of nonlinear equations, which are basic for the development of regulators of hydro- and aerodynamic processes parameters. Traditionally, approaches to the synthesis of regulators are based on the linearization of models, which allows the use of proven methods and algorithms during synthesis. However, at the stage of implementing the regulator at the facility, certain resources are spent, with the help of which the errors and stability of the regulation are evaluated or the regulator is adjusted at individual operating points of the operating range.

An alternative to the use of classic PID controllers used in linearized systems are fuzzy and neurocontrollers. The advantages of using the latter are manifested in cases when the object model is quite complex or its development is problematic. An additional convenience of using nonlinear regulators opens up when they are implemented in discrete computers in accordance with formalized criteria.

At the same time, neurocontrollers can realize their advantages (adaptability, robustness) only if they are adequately trained. At the same time, the process of "training" such a regulator usually requires no less resources than those spent on developing an accurate model. This refers to a number of experiments at the object, which are necessary for the formation of expert assessments.

Therefore, further studies of the expander turbine speed regulators are relevant.

2. Literature review and problem statement

The measures for the development of the overpressure expander turbine rotation speed regulator are based on the results of studies of the experimental installation for the utilization of excess gas pressure [1]. In this paper, it is shown that the plant (control object) is characterized by the non-linear nature of connections, both on the "input-output" channel and on the disturbance channels. The linearization of this model is carried out by obtaining a family of linear transfer functions for different operating points of the range, which allows to simplify the synthesis process of the turbine rotation speed regulator.

It should be noted that the mentioned model [1] is identified by the high order of the operator transfer function, which complicates the synthesis of control algorithms and their practical implementation for the studied plant. Considering the non-linear nature of the relationship between the parameters of this plant, the search for regulator synthesis methods is carried out in the class of adaptive regulators.

Although the ideology of constructing turbine operation regulators begins with the Watt regulator, research and their improvement continues in our time. According to the modern level of control theory, a non-linear model of the steam turbine control system was proposed in [2] and various regulators were investigated. It is shown that the most effective are the PID controller and the fuzzy PI controller. The combination of such regulators provides a reduction in the time of transient processes with minimal deviation of the turbine rotation frequency. The relevance of the introduction of alternative energy stimulates research in the field of wind turbines (WT), which are aerodynamically similar to expander turbines. Much attention is now being paid to the study of WT controls. In work [3] it is possible to see the use of a simple PID controller, with optimization by the integral of the quadratic deviation. When the tasks of control the interaction of generating WT with electricity consumption networks become more complicated, more complex control algorithms are proposed. Relying on achievements in the field of algorithmic and software tools, metaheuristic [4] or genetic algorithms [5] are becoming known, the efficiency of which has been shown in the construction of WT regulators. However, these ideas were not widely used, since it is quite difficult to take into account the variable operating conditions of the mentioned turbines.

The paper [6] proposes the use of a fuzzy PI controller, which increases the efficiency of WT control under conditions of changing wind speed and loads. At the same time, the use of a fuzzy PI controller requires the formation of an expert knowledge base, which requires more resources for its implementation.

In order to take into account the specifics of the operation of the WT, a fractional order controller (FOPID) was proposed in [7]. At the same time, two more parameters are added to the three parameters of the PID controller in the transfer function of the controller. These additional parameters are fractional order operators that are optimized using appropriate algorithms. However, for the practical implementation of the FOPID algorithm, it is necessary to solve the issue of approximating the function of the irrational FOPID controller by rational polynomials with integer degrees [8]. At the same time, the structure of the regulator is significantly complicated, which leads to a deterioration in the speed of calculations of controlling influences. That is, it can be stated that the practical implementation of the FOPID controller is possible only with the use of powerful computing tools. Therefore, the approaches proposed in [2, 4–8], despite their advantages, do not allow obtaining regulators that are simple for practical use.

To build a more feasible turbine speed regulator, it is advisable to use the approach proposed in [9]. In accordance with it, a reduced plant model is built, which allows synthesizing a simpler regulator. Similarly, work [10] investigates first-order linearized regulators that allow adaptation to different rotation speeds, i. e. torque moment disturbances. Adaptation is carried out by searching for the desired element of the settings table or using a flexible feedback controller.

All this gives reason to assert that there is a need to develop a method of constructing the EGU rotation speed regulator. This regulator should be suitable for its further implementation on widespread microprocessor automation tools.

3. The aim and objectives of the study

The aim of the study is to develop a method of constructing the EGU turbine rotation speed regulator. This will make it possible to implement the results obtained at the experimental installation for the utilization of excess pressure in the gas distribution industry, increasing the energy efficiency of gas distribution.

To achieve this aim, the following tasks were set:

– to get a description of the ECU in the form of a reduced mathematical model;

– to synthesize the EGU turbine rotation speed regulator using the obtained reduced transfer function;

– to implement the developed control algorithms based on the programmable logic controller (PLC) and evaluate the effectiveness of stabilizing the turbine rotation speed under the conditions of disturbances simulated in the experimental installation.

4. Materials and methods of the study

The object of the study is the EGU turbine, the mathematical description of which was obtained in the previous analysis of the control object [1]. The presence of the specified model makes it possible to formulate the control criteria necessary for the construction of a high-speed regulator implemented on microprocessor devices.

According to [1], the rotation of the expander turbine is determined by the following equations:

$$\tau_{Az}\frac{dA_Z}{dt}=-A_Z+U_\omega, \quad (1)$$

$$\tau_{tr}\frac{dQ_1}{dt}=Q_{dr}-Q_1, \quad (2)$$

$$\tau_T\frac{dP_2}{dt}=Q_1-Q_2, \quad (3)$$

$$Q_{dr}=\mu\cdot A_Z\cdot P_1\cdot\sqrt{\frac{k}{RT_1}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}},$$

$$Q_2=A_T\left(P_2-P_{2M}\right),$$

$$J\frac{d\omega_T}{dt}=M_U-M_{CL}-M_C, \qquad (4)$$

$$M_U=\left(P_2-P_{2M}\right)A_L R_L,$$

$$M_{CL}=K_{CL}\omega_T^{\ 2},$$

where τ_{Az}, τ_{tr}, τ_T – time constants, respectively, of changes in the cross-section of the valve, changes in losses in the pipeline, establishment of equilibrium between the input and output gas flows; μ – flow coefficient of the throttle section; ω_T – angular speed of turbine rotation; A_Z, A_T, A_L – cross-sectional area, respectively, of the throttle, the turbine outlet, and the flow of the gas flow; P_1, P_2, P_{2M} – pressure, respectively, of the pipeline inlet, at the turbine inlet, at the inlet of the low-pressure gas pipeline; Q_1 – gas flow rate at the turbine inlet; Q_2, Q_{dr} – gas flow rate, respectively, at the turbine outlet and at the throttle outlet; U_ω – turbine speed setpoint signal; M_C, M_{CL}, M_U – torque moment, respectively, of resistance to rotation, aerodynamic resistance of the medium during rotor rotation, turbine rotation; k – adiabatic index for gas; K_{CL} – aerodynamic drag coefficient; R – universal gas constant; R_L – radius of the turbine blades; T_1 – gas temperature in the inlet pipeline.

This system of equations corresponds to the modeling scheme of the expander turbine shown in Fig. 1 [1]. The model is a combination of three blocks, which reflect the dynamics of the electric drive of the throttle valve (1), the dynamics of the gas flow of the pipeline and the turbine (2), (3), as well as the dynamics of the rotation of the turbine shaft (4).

The non-linear nature of the connections in the plant does not make it possible to directly use the mathematical apparatus of the state space:

$$\frac{dX}{dt}=f\left(X,U\right), \qquad (5)$$

where X – vector of model states; U – scalar of controlling influences; $f(X, U)$ – vector function that characterizes the processes in the plant.

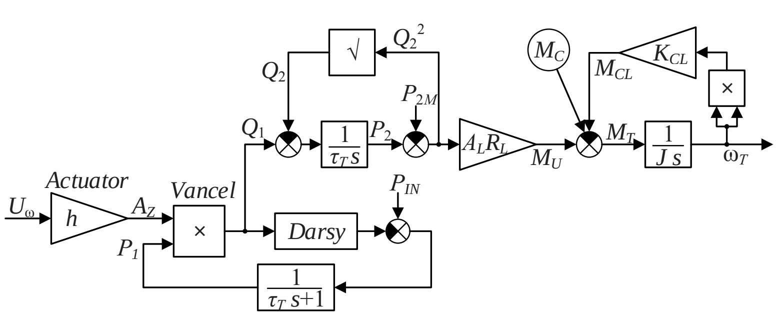


Fig. 1. Structural diagram of the expander-generator unit simulation

Since the methodology of using the state space has been developed for linear systems, the primary task of the regulator development is the linearization of the studied plant.

If the system of equations (5) is linearized with an acceptable error, then the obtained plant state space can serve as a basis for displaying the state vector of the model $X(t)$ at certain moments of time.

Let the initial value of the vector X at the moment of time t_0–$X(t_0)$, and its final state at the moment t_1–$X(t_1)$ be known. Let's believe that with the help of the controlling influence $U(t)$ it is possible to transfer the vector X from the initial state $X(t_0)$ to the final state $X(t_1)$. Then, the state regulator producing control $U(t)$ is required to minimize the time (t_1–t_0) at maximum gas flow rates Q.

Thus, the generalized control criterion has the form:

$$\underbrace{\min}_{T}\underbrace{\max}_{Q}=\left\{\Phi\left(P_{IN},P_{2M},A_Z,M_U\right)\right\}, \qquad (6)$$

where T – transition time.

The maximization of gas consumption is necessary to create a certain reserve for the turbine torque moment of rotation M_U in case of disturbances in the input and output gas flows.

At the same time, restrictions are imposed on the components of the state vector due to the technical capabilities of the utilization plant and considerations of physical meaning.

For example, the turbine torque moment of rotation M_U should not be less than the moment of resistance to rotation M_C. In addition, the pressure of the flow, its consumption, the turbine rotation speed cannot acquire negative values:

$$0\le\omega_T\le\omega_{T\max},$$

$$M_C\le M_U\le M_{U\max}, \qquad (7)$$

$$P_{2M}\le P_2\le P_{IN}.$$

An additional limitation arises from the operating conditions of the throttle drive, since mechanisms of constant stem movement speed H are used as an electric drive:

$$H_{\min}\le H\le H_{\max},$$

where $H_{\min}$ and $H_{\max}$ – minimum and maximum possible increase rates of the driving force.

It should also be taken into account that the range of linearity of each operating point of the linearized model [1] is limited to a certain value, which is determined by the design parameters of the plant.

Informal requirements for control consist in minimizing the impact of non-linearities of the plant under conditions of perturbations of gas flow parameters.

The control task is defined as adjusting the regulator parameters in real time according to criterion (6) under the conditions of disturbances of the gas flow parameters.

To build a PID controller, the method of root hodograph or Bode diagram is widely used, which are part of the MATLAB Simulink (USA) toolkit and are automated within this environment [11]. The use of the specified environment also speeds up the implementation of the obtained algorithms in the PLC [12], which is an additional argument in favor of its choice.

In [1], a linearized model of the studied plant is built, which is represented by a family of transfer functions (Bode diagrams). It makes it possible to construct a suitable family of logarithmic amplitude-frequency characteristics of the plant with closed feedback. Fig. 2 [1] shows how the expander turbine rotation model Bode diagram changes depending on the position of the stem h of the throttle valve.

The mentioned family of transfer functions is constructed in accordance with the family of plant "input/output" operator functions $G(s)$ according to the control influence [1]:

$$G_i(s)=W_{Mi}(s)*W_{Ti}(s), \tag{8}$$

where

$$W_{Mi}(s)=\frac{b_{1i}+b_{0i}}{s^4+a_{3i}s^3+a_{2i}s^2+a_{1i}s+a_{0i}} \tag{9}$$

–"flow rate/torque moment" transfer function;

$$W_{Ti}(s)=\frac{b_{0i}}{a_{1i}s+a_{0i}}, \tag{10}$$

W_{Ti} – transfer function "torque moment/rotation speed"; i – working point number; a_i, b_i – coefficients of transfer function polynomials.

This representation of the "input/output" transfer function is necessary to display disturbances in the moment M_C of resistance to turbine rotation (Fig. 1). These disturbances arise as a result of changes in the electrical load of the EGU generator.

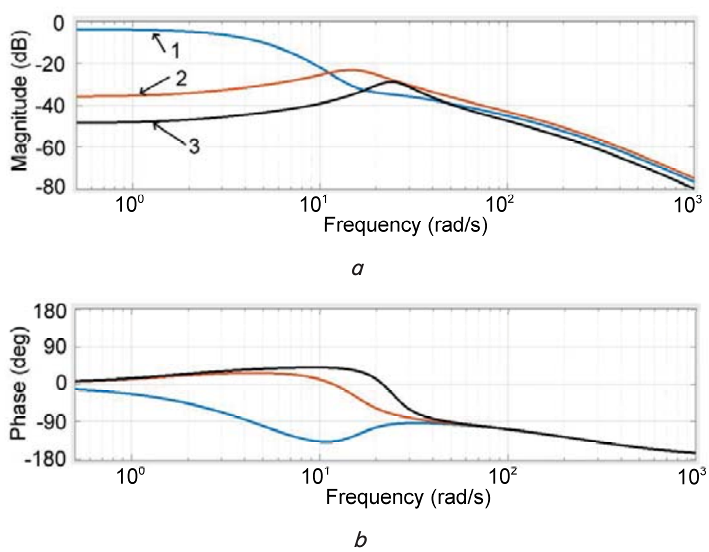


Fig. 2. Bode diagrams for different positions h of the throttle valve: a – amplitude-frequency characteristic; b – phase-frequency characteristic; 1 – h=4; 2 – h=10; 3 – h=16

Regulation of the turbine speed is carried out with the help of a compensator – a regulator, which is characterized by the transfer function $C_i(s)$. When the compensator is included in the rotation speed control circuit with a single feedback, let's get the general transfer function $W_K(s)$:

$$W_{Ki}(s)=\frac{C_i(s)G_i(s)}{1+C_i(s)G_i(s)}. \tag{11}$$

In order to realize the possibilities of automating the settings of the corrector C using the tools of the SISO Design Tool (USA), it is necessary to formalize the plant control criteria (6) and setting limitations (7).

The most common methods that allow obtaining the required stability and speed of transient processes in industrial facilities are based on the assessment of transient and frequency characteristics. At the same time, direct indicators of the regulation quality (overregulation, regulation time) are obtained from the transient characteristic.

Since generally accepted methods that allow setting the required stability and speed of transient processes in the system have not yet been worked out, the stability margin by phase is used as a stability indicator. The cut-off frequency of the frequency characteristic of the plant is used as an indicator of the speed of the transient processes of the plant (displayed on the transient characteristic). Corrective actions for adjusting the regulator parameters are displayed on the frequency characteristic of the investigated plant (Bode diagram) by means of graphic constructions.

Solving the problem of minimizing the value of the regulation criterion of type (6) makes it possible to calculate the coefficients of the compensator settings that provide the required regulation parameters.

It should be noted that the Ziegler-Nichols or Hrones-Reswick adjustment methods are not difficult to implement in practice, but are characterized by significant overshoots. Other methods provide the required accuracy only with typical objects of no more than second order.

Considering the order of the transfer function of the plant model (8), the expediency of reducing the order of this function is not in doubt. In addition, reducing the order of the transfer function makes it possible to increase the immunity and robustness of the control system.

Among the methods for reducing the order of the transfer function, those that allow for assessing the adequacy of the order change seem to be the most suitable. This is due to the fact that conventional discarding of high-order components gives inadequate results. Therefore, the correctness of decreasing the order of the transfer function is determined on the basis of criteria in the frequency or time spaces [13].

Specific steps to reduce the order of the plant model are based on the use of Hankel's estimate of singular values [14]. These numbers show the contribution of the various components of the state space variables that describe the behavior of the plant model. The *reduce* command of the MATLAB (USA) environment opens the way to model reduction procedures, which is formed using the MATLAB tool set [15]. The parameters of the reduction procedures should ensure the necessary accuracy of the approximation of the frequency characteristic of the plant in the frequency band close to the cutoff frequency.

The presence of a reduced-order plant model allows to proceed to the parametric synthesis of the compensator-regulator based on the criterion of the optimal module [15]. The meaning of the mentioned criterion is that the parameters of the system settings can provide minimal overshoot provided that the amplitude-frequency response (frequency response) of the closed system does not have a resonant peak. At the same time, the cut-off frequency of the frequency response must have a maximum value. The last requirement ensures the necessary speed of the system at the selected regulator settings.

However, this formulation of the optimal module criterion does not contain requirements for the phase stability margin, and the value of the cutoff frequency is presented as desirable.

If to specify the relationship between the requirements of the optimal module criterion and the frequency response parameters of the system, then the corresponding ratios will look like this:

$$\Delta\varphi(\omega_{3r})+\varphi_{CG}(\omega_{3r})=-\pi, \tag{12}$$

$$\frac{dW_{Ki}(\omega)}{d\omega}=\frac{d\left|C(j\omega)*G(j\omega)\right|}{d\omega}=0, \tag{13}$$

where $\Delta\varphi(\omega_{3r})$ – phase margin of the system at the cut-off frequency ω_{3r}; $\varphi_{CG}(\omega_{3r})$ – value of the frequency response phase "corrector – plant".

Condition (13) corresponds to the requirement of the absence of peaks in the frequency response of the open system, that is, the minimization of overshoots. The value of the deviation of the derivative (13) from zero will characterize the oscillation of the transient function of the system.

Ratios (12), (13) are used in the parametric synthesis of the $C_i(s)$ corrector in the SISO Design Tool (USA) environment. The obtained reduced transfer function $G_i(s)$ is accepted as the plant model.

At the same time, thanks to the Graphical Tuning option, the Bode diagram displays the results of adding correction links to the structure of the $C_i(s)$ corrector. Corrector parameters are determined by the location of zeros and poles on the Bode diagram (open circuit). The results of the settings are analyzed in the Analysis Plot option by the system closed circuit transition function. The transfer function of the $C_i(s)$ corrector is formed after analyzing the parameters of the transient function (astatism, overshoot, speed). The SISO Design Tool allows to obtain the coefficients of the corresponding PID controller only if the transfer function of the corrector $C_i(s)$ is rational.

In other cases of settings, when a complex structure of the $C_i(s)$ corrector is formed as a result of synthesis, it is problematic to implement a corrector, especially a PID controller, on microprocessor devices.

The settings of the regulator-corrector, obtained for a certain i-th operating point of the plant, due to its nonlinearity, do not provide the required quality of regulation at other operating points. Therefore, for other points of the operating range, the procedures described above are carried out to obtain the regulator coefficients.

Regardless of the type of controller selected, its adjustment coefficients for various operating points of the system are placed in the PLC memory in the form of a table [16]. In the case of disturbances in the parameters of the gas flow process or the load moment of the expander, the control program searches for the regulator coefficients that ensure the necessary accuracy of maintaining the turbine rotation speed.

Thus, the controller settings algorithm can be classified as adaptive. It consists in choosing the R_i-th regulator from the total number of n, each of which corresponds to the i-th operating point of the regulation range.

The primary task in developing the structure of the regulator is to estimate the approximation error of the plant model by the reduced order transfer function. Based on the histogram of Hankel functions, the transfer function of the plant model is given. With the help of the *reduce* command of the MATLAB toolkit, the transfer function of the reduced, in this case second, order is obtained in the form of state space matrices:

A=[–9.496–14.85; 14.85–0.7402];

B=[0.8284; –0.1936]; (14)

C=[0.8284; 0.1936];

D=0,

where A, B, C, D – matrices of the plant description in the space of states.

The transition from the state space to the Laplace transfer function is carried out by the command:

[b,a]=ss2tf(A,B,C,D),

where b – numerator; a – denominator of the desired Laplace transfer function.

As a result of the transition, the reduced plant transfer function is determined at a specific operating point of the channel range h/M. For example, for the operating point corresponding to the stroke of the valve stem h=10, the transfer function has the form:

$$W_{Mred}(s)=\frac{0.043s+0.98}{s^2+4.7s+65.3}. \tag{15}$$

The transfer function (15) of the section of the h/M model is combined with the transfer function of the turbine (first-order):

$$W_{Ti}(s)=\frac{500}{s+950}, \tag{16}$$

to form a control channel h/ω_T (Fig. 1), which is determined by the transfer function $W_{h\omega}(s)$:

$$W_{h\omega}(s)=W_{Mred}(s)*W_{Ti}(s). \tag{17}$$

This configuration of the h/ω_T channel is dictated by the need to model torque moment disturbances that occur as a result of changes in generator loads.

Using the Graphical Tuning option (SISO Design Tool), experiments were carried out to adjust the parameters of the $C_i(s)$ corrector based on requirements (12), (13). As a result of adjusting the frequency response parameters of the plant, the values of the sought coefficients of the corrector are obtained:

$$C_i(s)=\frac{K_i\left(s^2+4.7s+120\right)}{s*\left(s+11\right)^2}. \tag{18}$$

However, after performing the formal SISO Design Tool procedures described earlier, the practical application of the obtained PID controller coefficients for the plant model becomes problematic. The contradiction between the speed of the PID controller and the value of overshoot for the plant with signs of oscillation (Fig. 2) can be overcome only at certain values of the proportional coefficient.

Therefore, an alternative option for speed regulation is the relay regulator (RR), which has an "infinite" proportionality coefficient at the time of switching [17]. To build such a RR, the structure of a 3-position RR is adopted, the functional dependence of which on the control error ε has the form:

$$F(\Delta) = \begin{cases} U\max, \varepsilon > \Delta, \\ Uz, -\Delta < \varepsilon < \Delta, \\ -U\max, \varepsilon < \Delta, \end{cases} \quad (19)$$

where $U\max$ – value of the control signal; Δ – permissible control error.

The parametric synthesis of RR is usually performed with the help of a phase plane, where the level of stability of the plant model under step control influences is determined. Since the parametric synthesis of the plant RR is the subject of other studies, the following experiments on the study of the regulator were conducted in the direction of working out disturbances in the turbine rotation process. At the same time, it is considered that any stable and unstable oscillations are identified on the oscillograms of the speed control process.

Verification of the results of setting the RR speed parameters is carried out by the transient function of the rotation speed adjustment. At the first stage, the verification of disturbances of the turbine rotation process is carried out in the MATLAB Simulink (USA) model, the scheme of which is built according to the scheme of Fig. 1. To do this, in addition to the plant and RR models, a disturbance simulator, which is a signal generator of various shapes, is included in the model of the experimental installation of the EGU turbine. The adjustment of the RR parameters is carried out according to the criterion of the level of disturbances damping and the accuracy of maintaining the specified rotation speed.

The next stage of experiments was carried out on the experimental installation, the general view of which is shown in Fig. 3. The revolutions of the turbine 6 depend on the position of the valve 3, which is positioned by the stepper motor 2. The results of the control of the flow of compressed air coming from the pressure source 4 and controlled by the regulator 5 are displayed on the process monitor 1. Disturbances of the torque moment, on which the rotation speed depends, are simulated by changing the load of generator 7 and the load regulation scheme.

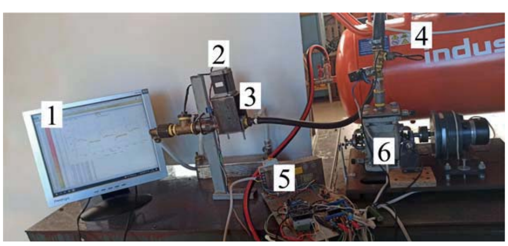


Fig. 3. View of the experimental installation:
1 — process monitor; 2 — stepping motor; 3 — throttle valve; 4 — pressure source; 5 — regulator; 6 — turbine; 7 — generator

Changing the load (alternating braking/rotating cycles) was carried out by changing the electrical load of the generator connected to the shaft of the controlled turbine. Load jumps correspond to the real conditions of consumption of electrical energy, which is issued from the generator to the consumption network.

The main content of the research at the installation is obtaining experimental data on the dynamics of the real plant and the positioning accuracy of the adjustable valve. These data are necessary for the construction of the "constant speed executive mechanism" regulator, given that a stepper motor is used as a device for electric drive of the throttle. In addition, the results of natural modeling should confirm the validity of the assumptions made during the construction of the mathematical model.

5. Results of the development of the speed regulator construction method

5. 1. Results of the expander-generator unit mathematical model reduction

The Hankel singular values histogram obtained in the MATLAB environment (Fig. 4) allows to draw a conclusion about the expediency of reducing the transfer function of the plant channel h/M (9) to the second order.

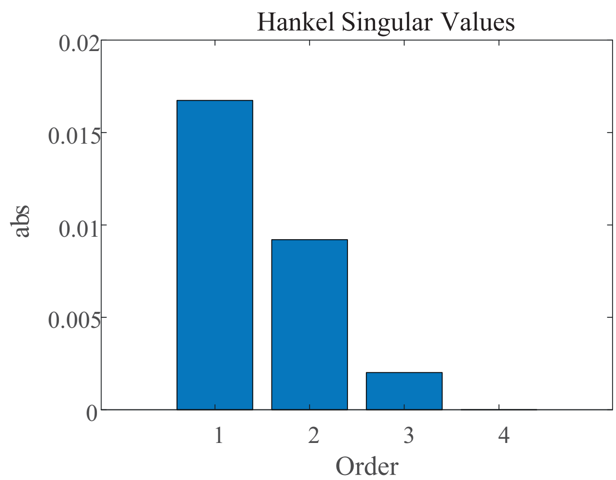


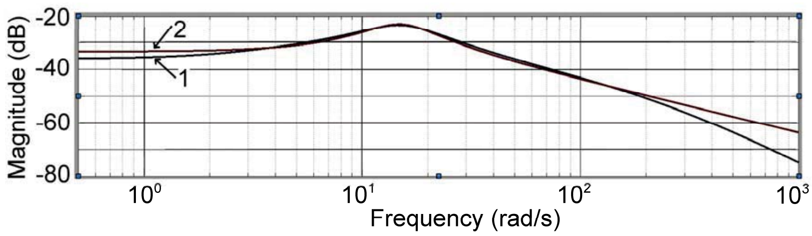
Fig. 4. Hankel singular values histogram for the expander-generator unit model

The approximation error of the transfer function (9) by the reduced transfer function (15) is illustrated by the Bode diagram shown in Fig. 5.

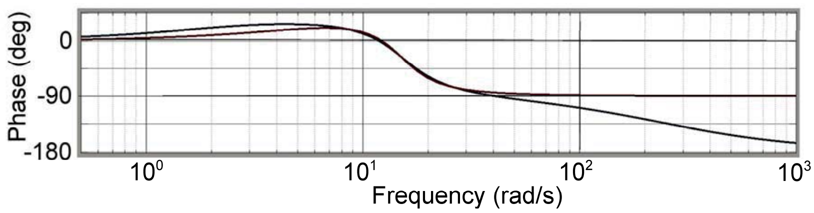
From the diagram Fig. 5, it can be seen that decreasing the order of the transfer function preserves the coincidence of the characteristics at the inflection point in terms of value and derivative. No significant approximation errors are observed in other sections of the frequency band up to 200 rad/s.

The resulting reduced EGU model in the form of transfer function (15)–(17) is implemented in the MATLAB Simulink environment. The dynamics of the turbine rotation process, which is observed in the valve opening/closing processes, is shown in Fig. 6.

It can be seen from the oscillogram that the change in the direction of movement of the valve is accompanied by damping speed oscillations.



a



b

Fig. 5. Bode diagram of an open system (1 – function (9); 2 – function (15)): *a* – amplitude-frequency characteristic; *b* – phase-frequency characteristic

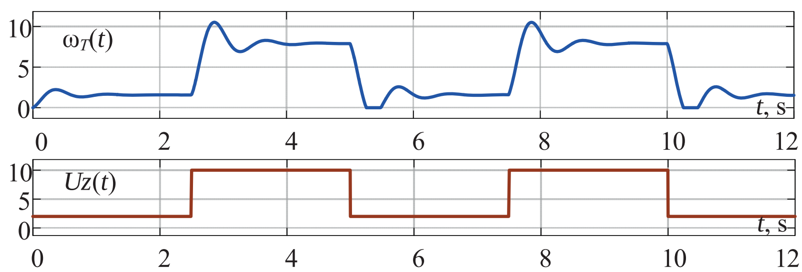


Fig. 6. Graphs of changes in rotation speed $\omega_T(t)$ and control influence $Uz(t)$

The oscillogram (1) demonstrates the operation of the turbine without a regulator and actually repeats the one in Fig. 6. The oscillogram (2) obtained under the same conditions of changes in the control influence demonstrates the influence of the RR on working out the change in the speed setpoint. In turn, the oscillogram (3) shows the quality of rotation speed stabilization for the RR system when the load changes (4).

5. 2. Results of synthesis of the regulator and examination on the model

As mentioned, it is difficult to synthesize a PID controller with the desired parameters for the plant, therefore, a three-position RR (19) is used in the investigated plant mathematical model. The results of modeling the operation of the synthesized RR is showed in Fig. 7.

5. 3. Results of the regulator implementation on the experimental installation

In order to evaluate the effectiveness of the RR and the validity of the accepted assumptions during system modeling, the RR of the turbine rotation speed was implemented in the experimental EGU installation based on Siemens Simatic S7-300 CPU 314C-2DP (Germany) PLC. The result of speed regulation is illustrated by oscillograms obtained on the process monitor (Fig. 3). The oscillograms of the change in rotation speed when the electromechanical loads change are shown in Fig. 8.

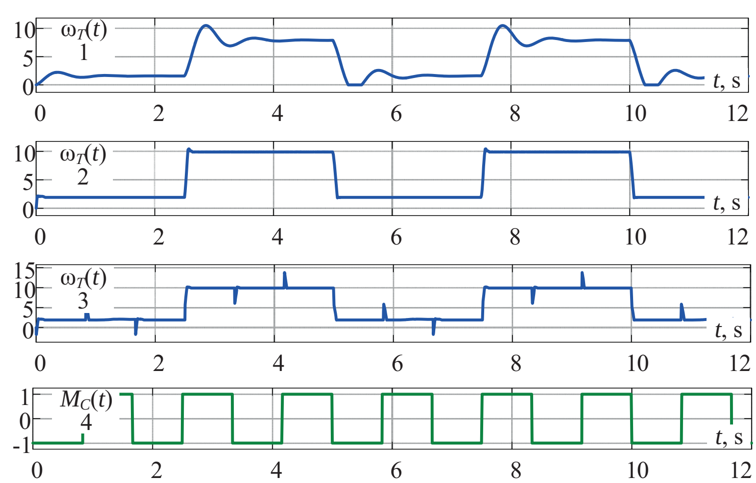


Fig. 7. Graphs of change: 1 – speed $\omega_T(t)$ without a relay regulator; 2 – speed $\omega_T(t)$ with the relay regulator turned on; 3 – speed $\omega_T(t)$ when the load changes; 4 – load $M_C(t)$ change graph

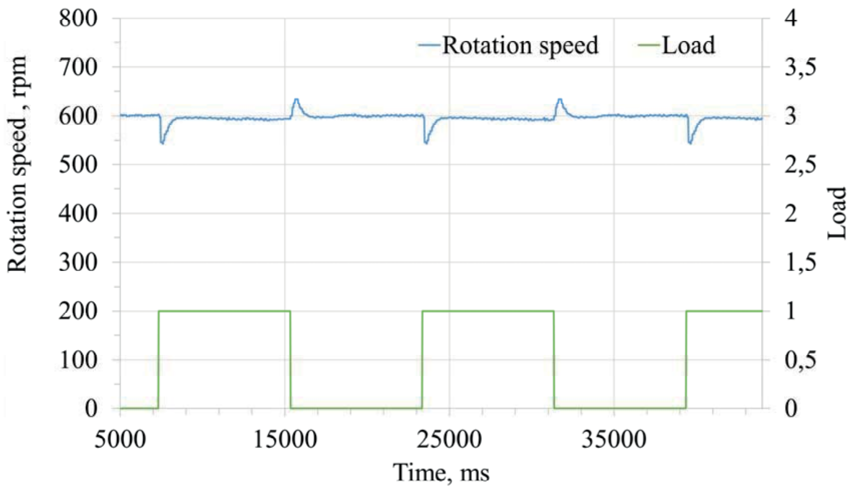


Fig. 8. Oscillograms of changes in turbine speed and load

From the oscillograms of Fig. 8, it can be seen that as a result of the control, a mode of automatic speed oscillations is established, the amplitude of which depends on the RR settings. An important result of the research is the stabilization of the turbine rotation speed, which affects the parameters of the electricity generated by the EGU electric generator.

6. Discussion of the results of the development of the regulator construction method

The obtained reduced mathematical model (15)–(17) quite accurately approximates the initial transfer function of the EGU turbine, which can be seen from Fig. 5. At the same time, the speed oscillations observed in the graph of Fig. 6, is a consequence of the presence of a local maximum at the frequency response of the plant transfer function (Fig. 5).

When choosing approaches to the development of the EGU turbine rotation speed regulator, studies of objects that are similar in terms of their functioning principles were taken into account. These include steam and hydro turbines, as well as wind turbines. All these objects are characterized by nonlinear models that describe them. The conducted studies revealed difficulties in the application of the classic PID controller to control the EGU turbine. First of all, this is due to the limitation of the dynamic characteristics of the constant speed executive mechanism, which is the actuator of the pipeline valve. These limitations stem from the design features of the investigated plant. Additional complexities of settings are caused by the nonlinearity of the plant parameters, even at the selected operating point of the model, since the blocks of the investigated plant model have a different nature of nonlinearity. One of the ways to overcome these difficulties is the use of intelligent regulators. However, this requires additional computing resources and additional costs for the formation of an expert knowledge base about the plant [18, 19]. The proposed 3-position RR (19) provides the possibility of simple adjustments to the parameters of a specific installation and stabilization of modes in the event of disturbances in the parameters of the gas flow (Fig. 7).

The results of the research (Fig. 8) on the experimental setup (Fig. 3) allow to assert that the use of the proposed RR allows obtaining acceptable regulation dynamics. These stabilization parameters are achieved due to the use of a fairly accurate sensor of the turbine rotation speed and microprocessor controls of the throttle valve actuator.

The limitations of the study include the relatively small capacity of the equipment of the experimental installation. In further research, it is planned to use a brushless motor (BLDC) as an electric drive of the throttle. This will make it possible to control the gas flow not only in utilization facilities, but also in more powerful pipelines. Replacing the design of the executive device will affect the plant dynamics and the parameters of its model. However, the research methods of the low-power turbine model can be used to build regulators of other turbines of this type, or turbines of small hydropower plants.

The proposed regulator is supposed to be used as an internal control circuit of the EGU. At the same time, the task of increasing the efficiency of the entire installation is assigned to the external control circuit of the EGU. Increasing the stability of the turbine rotation in the presence of disturbances with the use of the proposed RR will make it possible to reduce the rigidity of the requirements for the "turbine – electric generator" system parameters regulator. The importance of this achievement lies in the possibility of compensation for random disturbances coming from the consumption network.

7. Conclusions

1. The approach to the synthesis of a family of PID controllers for a set of operating points of the control range, depending on the operating mode of the EGU, was proposed. Corresponding families of reduced plant transfer functions were built, each of which reflects the dynamics of the operating point of the selected control range.

2. Research on the EGU model showed that the presence of interconnected processes with various types of nonlinearities in the plant does not allow for adequate adjustment of the PID controller. For the construction of the turbine rotation speed regulator, the criterion of "minimum fluctuation of the parameter when changing its set value" is proposed. As a result, a 3-position relay regulator was built for a non-linear object with signs of oscillation. This made it possible not only to reduce rotation speed fluctuations to 5 %, but also to minimize the impact of rotation process disturbances.

3. Experimental studies on a laboratory installation confirmed the results of modeling the operation of the EGU with a relay regulator. In accordance with the set task of the practical implementation of the microprocessor *controller*, the speed of control influences was estimated, which was 1 ms. The relatively simple algorithm of the proposed regulator simplifies its implementation in a microprocessor control

system, in contrast to much more complex FOPIDs [8, 20] or neurocontrollers [18, 19].

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The work has no associated data.

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