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OPTIMAL GAS TRANSPORT MANAGEMENT TAKING INTO ACCOUNT RELIABILITY FACTOR

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Abstract:
In the period of shortage of gas supply, special attention is given to reducing the supply of gas to its consumers, that is, their complete and uninterrupted gas supply. Increasing gas losses associated with technological transportation costs, in particular caused by gas flow instability and frequent changes in gas transmission network operating modes. Considering losses due to unreliability of gas pumping is one of the important tasks of gas supply optimization. The purpose of the study is to develop an optimization mathematical model that will simultaneously take into account the factors of reliability and minimum lossesIn the general case, the optimization calculations of the modes of operation of the main gas pipelines are intended to solve three main problems: determining the maximum productivity, calculating the optimal mode with a given productivity and choosing the optimal strategy, the development of the pipeline. On the basis of approaches of simulation modeling of complex systems, a multiparameter mathematical model of gas supply process optimization was developed. It is shown that a comparative analysis of the forecast and actual indicators of the operating modes of the plunger gas pumping unit shows their satisfactory convergence. The performance of the compressor operation period in the process of injection according to the forecast deviates from the actual value for the whole period of operation of the plunger gas pumping unit in 2016 by 2.98%. The optimization problem of gas pumping planning is considered, taking into account the expected losses, on the basis of which the transfer of the controlled system from the initial state to the final one is carried out by such a sequence of states that minimizes the total cost of the system evolution.

Key words: *optimization of gas supply, reliability, simulation modeling, technological losses*

NOMENCLATURE

P_{Ni} – inlet pressures of the i-th compressor station;
P_{Vi} – outlet pressures of the i-th compressor station;
Q_i – the performance of gas pumping units;
R_i – the number of gas-pumping units;
N_i – total capacity;
P_{Hmax} – the maximum allowable pressure due to the durability condition of the pipeline;
P_{Bmin} – the minimum allowable pressure from the condition of normal operation of gas-pumping units;
n_i – the rotation of the rotor of the pumping units;
$M_l(t_1,\ t_2)$ – mathematical expectation of the fraction of time;
$P_i(t_i)$ – the probability that the at the moment;
Δt – a time step;
λ_{ji} – the intensities of transitions from state i to state $i + 1$;
C^n – cost losses;
C_1 – coefficient;
H – lack of gas to consumers;
C_2, C_3 – coefficients that take into account the cost of pumping and underfilling;
u_{ij}^n – discrete change in losses over time;
A_j – coefficient taking into account the distribution of losses under normal law;
Q – the performance of the pipeline;
m_r – coefficient allowing to eliminate non-working elements equal to 1 or 0;
G_0 – the amount of pumped gas;
ε_i – the degree of pressure increase;
N_i – power of the unit;
η_i – coefficient of performance;
C_i – specific costs;
Φ_0, Φ_N – costs for the initial and final state of the system;
$F_N(j)$ – Bellman function;
Q – compressor station performance;
P_{out} – pressure at the outlet of the compressor station;
P_{in} – pressure at the inlet to the compressor station;
nn – nominal revolutions;
N_{ef} – determined by the proposed optimization method.

INTRODUCTION

In the period of shortage of gas supply to Ukraine, special attention is given to reducing the supply of gas to its customers, that is, their complete and uninterrupted gas supply.

On the other hand, gas losses associated with technological transportation costs are increasing, in particular, caused by the unsteady flow of gas and frequent changes in the modes of operation of the gas transmission network [22, 23].

It is known that losses from gas shortages to consumers far outweigh the losses associated with technological costs of gas transportation [6, 8, 9, 16, 17]. Therefore, the problem of choosing the optimal ratio between the cost and reliability of gas pumping is considered here. This problem is investigated using a mixed model based on the use of dynamic programming methods and mathematical methods of reliability theory.

LITERATURE REVIEW

Optimization of the modes of operation of gas transmission systems and management of their operation is devoted to a number of works [1, 2, 3], which discusses the choice of optimality criteria, the construction of the purpose function, the method of its practical implementation, the principles of the choice of control factors and influences. In particular, it is shown that the maximum economic effect is achieved by maintaining pumping volumes at the system throughput level, ie at full load, which requires maintaining operating pressures at the maximum permissible level. On the other hand, as noted in studies on the reliability of gas supply systems [4, 5], high operating pressures and limiting capacities of gas-pumping units contribute to an increase in the rate of aging of pipelines and equipment, which ultimately leads to an increase in the accident rate and its consequences (increasing costs emergency repairs, gas losses during transportation, pollution).In the general case, the optimization calculations of the modes of operation of the main gas pipelines are intended to solve three main problems: determining the maximum productivity, calculating the optimal mode with a given productivity and choosing the optimal strategy, development of the pipeline [6, 11]. When planning regimes in calendar cycles, the results of statistical processing of information on the actual state of the pipeline as a whole for any period of time, as well as the results of solving forecasting problems are used as the output data [1, 13, 21]. To make operational calculations, information on the actual state of the pipeline at the necessary times is required. Recently, gas transport system (GTS) loading has been declining, which may lead to gas shortages for consumers, so new problems arise for the operating organizations and in some cases it is necessary to review the principles of system management [3, 7, 12, 14, 16].

To meet the requirements of maximizing the load of the gas transmission system with appropriate technological constraints and guarantee continuity in the delivery of a given gas consumption to consumers. These three problems are closely linked. In this regard, these problems are combined under the common name of planning of gas pumping [12, 13, 16, 21]. At the same time, polycriteria optimization was not performed in terms of reliability and minimum losses. Therefore, the purpose of this study is to develop a mathematical model that takes into account both factors.

METHODOLOGY OF RESEARCH

Methods of analysis of gas supply elements can be divided into theoretical (mathematical), experimental and experimental-theoretical. Theoretical analysis can be analytical or numerical, carried out with the help of modern computer systems.

In the first case, the results are obtained in the form of formulas that allow to trace the dependence of the original coordinates on the initial data, the structure of the system and its parameters quite simply and clearly. The greatest difficulties arise in finding the numerical values of the coefficients of the obtained equations [18, 20]. For this purpose it is necessary to know in advance the element geometry, the speed of movement, the coefficients of heat transfer, etc. The criterion for the correctness of the complex equations is a coincidence with a certain accuracy of their numerical decisions with the operational data [4, 10, 19, 20].

Mathematical model of gas supply processes means a set of equations describing a technological process in a stationary or non-stationary mode. Stationary models describe the nature of the relationship between input x and output in the values of the elements of the gas supply system in the installed and in most cases are equations of the type $y = f(x1, x2,…, xn)$. The function f is often nonlinear. Most often, gas preparation processes are described by ordinary differential equations, and gas transport processes by partial differential equations. In many cases, it is advisable to use integral equations if necessary [2, 18]. With small changes in the input coordinates x1, x2, ..., xn, the nonlinear function f can be linearized, which is often used, for example, in gas equations. The steady-state equations are generally contained in the non steady-state equations and can be obtained by zeroing all the derivatives in time.

The main advantage of experimental research is the elimination of sources of errors related to the lack of a priori information when drawing up an analytical model of the elements of the gas supply system [8, 9, 12, 17, 19]. However, the possibilities of the experimental methods are limited by the narrow range of initial data and, most importantly, the practical impossibility in some cases of reproduction of the results of the experiment in operational conditions or close to them due to the big economic losses or the duration of the experiment.

In laboratory studies, some elements are replaced by their mathematical models, and therefore research is often reduced to experimental and theoretical [6, 11, 12, 17]. Most often, for the design and operation of long-distance gas transportation systems, all methods are used: in the initial stage, most often - theoretical studies, then - laboratory and, finally, semi-production and production tests.

For tasks of dispatching control of gas supply systems it is necessary to have a mathematical description of gas supply processes obtained by this or that method. Any element of the gas supply system is characterized by input and output parameters that can be controlled and unmanaged. Some technological, economic and, from the point of view of fire risk, safety restrictions are imposed on both. There are also a number of external factors, most often random ones, that also need to be considered in mathematical description.

Two methods of mathematical description are used: the first is based on the receipt of physicochemical laws, the second – on the theoretical possibility of describing the process with the help of certain formal mathematical expressions.

The first method is based on a careful study of the processes of heat and mass transfer in the elements of gas transmission systems. The mathematical description in this case consists of the equations of material balance, thermal balance, etc. For example, in the simple case of gas motion through the pipes is described by the equation, which includes the equation of conservation of the amount of motion and the equation of conservation of mass.

In the second method, empirical mathematical dependencies are used for mathematical description. For example, the viscosity formula of non-Newtonian fluids offers more than a dozen empirical dependencies. Often, the theory of similarity in its pure form cannot be applied to the processes occurring in the elements of the gas transmission, for example, to the processes in the gas-drying apparatus by sorbents. Therefore, formal empirical regularities obtained for laboratory facilities cannot be used without further research to calculate industrial installations. The mathematical description is based on physicochemical laws, adequate to the technological process.

Therefore, it is advisable to use the second method in the absence of a priori information about the structure of the system and the physicochemical processes occurring in it, to evaluate the limits of the use of analytical methods, and in the case of high complexity of analytical description, to obtain simpler analytical expressions. The problem of determining the mathematical description in the elements of gas transport systems in the stationary (static characteristics) and non-constant (dynamic) modes is a problem of identifying the characteristics of the elements of gas transport systems. Its solution consists of: choosing a method based on the specific operating conditions of the gas supply element and the available a priori information on its properties; the choice of operating conditions and actions for this item under which the experimental data should be recorded; processing of experimental data to determine the desired characteristics; estimates of accuracy, etc.

A complete mathematical model of the system consists of a description of the relationships between the parameters of the technological process:

- for compressor stations

$$F_1(P_{\mathrm{Bi}}, P_{\mathrm{Hi}}, Q_{\mathrm{i}}, R_{\mathrm{i}}, n_{\mathrm{i}}, N_{\mathrm{i}}) = 0 \quad (1)$$

- for linear sections

$$F_2(P_{\mathrm{Hi}}, P_{\mathrm{Bi+1}}, Q_{\mathrm{i}}) = 0 \quad (2)$$

where:

P_{Ni}, P_{Vi} are the inlet and outlet pressures of the i-th compressor station, the capacity of which is Q_i, R_i is the number of gas-pumping units at the i-th compressor station operating at rotor rotation ni, with a total capacity of N_i.

The operating mode parameters are restricted:

- for pressure

$$P\mathrm{i}_{\mathrm{H}max\,\mathrm{B}min} \quad (3)$$

where:

P_{Hmax} is the maximum allowable pressure due to the durability condition of the pipeline;

PBmin is the minimum allowable pressure from the condition of normal operation of gas-pumping units;

- for the performance of gas pumping units

$$Q_{\mathrm{i}} \geq 1.1 \cdot Q_{min} \quad (4)$$

where:

Q_{min} is the lowest possible performance against surge prevention;

- for the rotation of the rotor of the pumping units

$$n\mathrm{i}_{max\,min} \quad (5)$$

where:

n_{min}, n_{max} are the limits of the technologically permissible rotation of the drive rotor of the unit with a maximum power $n < n_{max}$.

As a criterion of optimality it is proposed to use energy costs for transport and conditions for ensuring a given level of reliability of gas supply.

This information is used as the output for the procedure for optimizing the control of the mode of gas transportation, the schematic diagram of which is given below.

RESULTS

The complete model of the system consists of a mathematical description of the relationships between the main variables of the technological process process in the stationary and non-stationary modes, technological, economic and other process constraints. Often, in the case of complex systems, the criterion of optimal performance.

In order to solve the problem of optimal planning of gas pumping, the expected losses are first of all sought due to the lack of reliability of gas supply to consumers [4, 10, 19, 20]. Gas supply failures are caused by the random nature of the system functioning, which are manifested in the failure of individual elements, as well as in the random fluctuation of the system load. Each unit of the system in the process of operation may be in a state of failure and in a state of operation with partial loss of output power. The system state probabilities are represented as the product of the state probabilities of the individual elements.

Let $M_l(t_1, t_2)$ mathematical expectation of the fraction of time of finding the system in state l during the interval, then

$$M_l(t_1, t_2) = \frac{1}{t_1 - t_2} \int_{t_1}^{t_2} P_i(t_i)dt \quad (6)$$

where:
$P_i(t_i)$ is the probability that the at the moment,
t_i system is in state i.
The probabilities of states of the entire system consisting of R aggregates in the discrete form will have the form

$$P_i(t_i) = \prod_{r=1}^{R} P_{r_i}(t) \quad (7)$$

If, $t = n\Delta t$
where:
Δt – is a time step, then expression (2) will take the form

$$P_i(n\Delta t) = \prod_{r=1}^{R} P_{r_i}(n\Delta t)$$

Then integral (1) can be represented in a discrete form

$$M_l(t_1, t_2) = \frac{1}{N}\sum_{n=0}^{N} \frac{P_i(n\Delta t)+P_i(n+1)\Delta t)}{2} = \frac{I_i(t_1,t_2)}{(t_1-t_2)} \quad (8)$$

The expected number of transitions to state i in the time interval (t_1, t_2) is determined by the formula

$$F(t_1, t_2) = \sum_{j\neq i} \int_{t_1}^{t_2} P_j(t)\lambda_{ji} dt \quad (9)$$

where:
λ_{ji} – the intensities of transitions from state i to state i + 1, $j = i + 1$.
In a discrete form we have

$$F(t_1, t_2) = \sum_{j\neq i} \lambda_{ji} I_i(t_1, t_2) \quad (10)$$

Suppose that a certain number of R units are allocated for gas pumping over a time interval and the estimated pumping amount is. Suppose that to pump gas for a time interval (t_1, t_2) a certain number of R units are allocated and the estimated pumping amount is G0.
During the specified time interval, the true load may vary in magnitude according to the normal law of distribution. Insufficiency in gas supply resulting from the failure of some units and due to accidental disturbances can theoretically vary from 0 to G (in practice, the range of gas shortage changes is quite narrow due to the accumulating capacity of the pipeline). Therefore, it is assumed that the relationship between total cost losses and the amount of gas shortage is linear

$$C^n = C_1 H \quad (11)$$

where:
C^n – cost losses,
C_1 – coefficient,
H – lack of gas to consumers.
Under the normal law of distribution of random variables, the total losses are summed up as losses on pumping and losses due to under-supply of gas. These losses can be reported as follows

$$W = C_2 \sum_j \sum_i [\sum_{j\neq 1} \lambda_{ji} I_{ij}(t_1, t_2)] u_{ij}^n A_j + C_3 \sum_j \sum_i I_{ij}(t_1, t_2) H_{ij} A_j \quad (11)$$

where:
C_2, C_3 – coefficient that take into account the cost of pumping and underfilling;
u_{ij}^n – discrete change in losses over time;
ΔtA_j – coefficient taking into account the distribution of losses under normal law.
The amount of pumped gas G0, these losses and the lack of H take discrete values at intervals $n\Delta t$, where the number of possible values of H depends on the number of states of the whole system, and each state corresponds to a certain value of the power of combinations of units. To do this, you can use an approximate method of calculating the system capacity, based on the same type of pressure drop equations for different elements. As a universal equation for the unit can be used expression

$$P_i^2 - \alpha P_j^2 = \phi Q_{ij} + \psi {Q_{ij}}^2 \quad (12)$$

where:
Q is the performance of the pipeline.
This equation is also used to equilibrate groups of compressor station units in parallel, which is a common GPU connection. The coefficients α, ϕ, ψ are the parameters of the rth unit that are known; – the pressure at the inlet and outlet of the r-th unit, ie

$$P_{1r}^2 - \alpha_r P_{2r}^2 = \varphi_r Q_{ij} + \psi_r {Q_{ij}}^2 \quad (13)$$

$$Q = \sum_{r=1}^{R} m_r Q_r \quad (14)$$

where:
r is the GPU number in the group;
R is the number of GPU in the group;
m_r – coefficient allowing to eliminate non-working elements equal to 1 or 0.
For two consecutively connected elements, the coefficients are equivalent
$\alpha = \alpha_1\alpha_2; \varphi = \varphi_1 + \alpha_1\varphi_2; \psi = \psi_1 + \alpha_1\psi_2$
The resulting equations do not fully determine the capacity of the system due to the limitation on the performance of each unit, so it is advisable to reduce them to a different type with respect to the cost of pumping

$$f_1(Q) = f(\varepsilon_i, N_i, \eta_i, n_i, C_i) \quad (15)$$

where:
ε_i – the degree of pressure increase;
n_i – power of the unit;
η_i – coefficient of performance;
n_i – speed;
C_i – specific costs.
Marking a_r, b_r the lower and upper limits of the output power of each unit, we have,

$$A_R \leq G \leq B_R \quad (16)$$

where:

$$A_R = min(a_1, a_2., \ldots, a_r); B_R = \sum_{r=1}^{R} b_r \quad (17)$$

From the consumption graphs, the upper and lower bounds of the required amount of gas for the k consumer can be obtained at each step of the calculation. Then the minimum cost per unit of time is the optimal recurrence ratio:

$$f_R(G) = min\{f_R(x) + f_{R-1}(G-x)\} \quad (18)$$

where:
x is the current amount of pumped gas.
If, ε_i, n_i, η_i – are constant values, then the use of the last relations gives the optimal scheme of separation of units and load distribution between them. With consistency, ε_i, η_i, n_i, you can get optimal control by changing the speed n_i.
Taking into account losses due to unreliability of gas pumping, the task of optimal planning is presented as follows. For the forecasted daily intake, the 24-hour segment is divided into 12 intervals, so one can assume that the impressions are considered permanent. We call these intervals stages. A gas pumping program is defined at each stage, which minimizes the total pumping costs, taking

into account gas supply reliability. Dynamic programming method is used to solve this problem. If you set R units on the compressor station, then the total number of possible combinations of units is R, where you can get the dimension of the dynamic programming problem.
At each stage, f_{nj} the cost of pumping gas at the jth combination of units at stage n_j; W is the expected loss due to a lack of gas when using the combination j in step n_j.
The minimum cumulative cost f_{nj} for combination j in step n_j can be found using the recurrence relation

$$F_{nj} = min\{ F_{n-1} + f_{nj} + W_{nj}\} \quad (19)$$

For the first step $n = 1$, the optimal combination is determined by the expression

$$F_{1j} = min\{ f_{1j} + W_{1j}\} \quad (20)$$

After all n steps have been completed, the minimum total cost of gas pumping is determined from the equation

$$F_N = min\, F_{Nj} \quad (21)$$

DISCUSSION

The solution of the problem of discrete dynamic programming is carried out using the standard algorithm. The idea behind the algorithm is as follows.
The sequence of moments of time 0, 1, 2 is considered.
The managed system can be in one of j states at any given time. Management of the system, which is at time n in the state, j_n is that a decision is made to translate it at the time $n + 1$ in the state. Determined the local cost of such a transition, that is, the number (for all possible pairs j_n, j_{n+1}).
At the initial time $n = 0$, the system may be in some fixed state. At time N, the system must be in one of the specified j_0 states. The task is to determine such a sequence of states (trajectories), f_0, f_1, ... f_n, ... f_N, ... that minimizes the total cost of the system's evolution, that is, the function

$$R(f_0, f_1,...,f_N) \;\; = \Phi_0(f_0) + \sum_{n=0}^{N-1} f_{j_n,j_{n=1}}^{n+1/2} + \Phi_N(j_N) \quad (22)$$

where:
Φ_0, Φ_N – costs for the initial and final state of the system.
The solution of the problem is carried out by a special algorithm, which uses the typical Bellman function $F_N(j)$, which is defined as follows: let the system at state n be in state j. Need to translate it to N, minimizing by selecting states of value f_{n+1}, ... f_N.

$$\sum_{n=0}^{N-1} f_{j_n j_{n=1}}^{n+1/2} + \Phi_N(j_N)\,,\; j_N = j \quad (23)$$

The minimum of (10) is by dynamic programming methods, which results in the calculation of the function $F_N(j)$ for all n and j. This equation is obtained on the basis of the following principle of optimality: the transition from state j at time n to some state at time N can be done in two steps. First, the system is transferred to the state at the time $n + 1$, and then from this state in the optimal way for the price $F_{N+1}(j)$ – in the final state. The total cost of such a transition is

$$f_{j_n i}^{n+1/2} + F_{n+1}(i) \quad (24)$$

Since it j is considered fixed, the optimization parameter is the status number i at time $n + 1$. Then the dynamic programming equation will be

$$F_n(j) = min\{ f_{j=i}^{n+1/2} + F_{n+1}(i)\} \quad (25)$$

Thus, having found al $F_N(j)$, we solve the problem $min\{\Phi_0(j) + F_0(j)\}$ and determine the first point of the trajectory j_0. Then determine the points, $j_1 = i_{1/2}(j_0)$ $j_2 = i_{1+1/2}(j_1)$ and so on to plot the entire trajectory.
On the basis of the described methodology of forecasting the optimal parameters of the gas supply regime, taking into account the factor of reliability, calculations of optimization of operation of the compressor station of Bogorodchansky underground gas storage (UGS) for August 24, 2017, of the period of compressor injection of gas into the storage were carried out.
It should be noted that in the simulation, it is considered that the modes of gas motion in all parts of the gas supply system are stationary and isothermal. In the calculation of gas compression, the determination of power is made for each of the operating units, the number of which is determined by the performance and is taken as integer.
The initial data for the realization of the set optimization problem were the real indicators of operation of the compressor station during the gas injection into the storage:
Q – compressor station performance;
P_{out} – pressure at the outlet of the compressor station;
P_{in} – pressure at the inlet to the compressor station.
As a result of the calculations, the optimal number of compressor cylinders and their capacity N_c, the relative speed of rotation of the crankshaft n/*nn* (*nn* – nominal revolutions) and the effective power of the compressor station N_{ef} were determined by the proposed optimization method. When predicting a rational mode, there is not the absolute value of power consumption, but the dynamics of its change, so the results of the calculations are given in relative terms (Fig. 1).

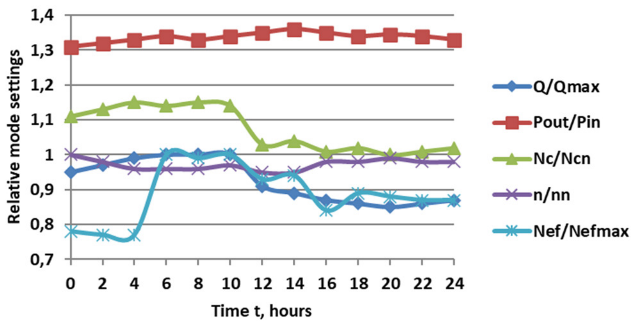

Fig. 1 Results of calculation of optimization of operation of the compressor station of Bohorodchany UGS

The forecast parameters were introduced into production and their comparison with the actual ones showed satisfactory convergence (Table 1).

Table 1
Real and predictive parameters of compressor station

t, hours	Q, Th m³/hour	P_{out}, at	P_{in}, at	P_{out}/P_{in}	n, rpm	N_c, h.p.	N_{ef}, Th hp
	Measured parameters				Forecasted parameters		
0	377	97.2	74.2	1.31	300	668.2	19.7
2	385	97.2	73.6	1.32	294	680.3	19.4
4	393	97.3	73.2	1.33	288	692.3	19.4
6	397	97.3	72.6	1.34	288	686.3	25.2
8	397	97.3	73.2	1.33	288	692.3	24.9
10	397	97.4	72.7	1.34	291	686.3	25.2
12	361	97.4	72.1	1.35	285	620.1	23.4
14	353	97.5	71.7	1.36	285	626.1	23.7
16	345	97.5	72.2	1.35	294	608.0	21.2
18	341	97.5	72.8	1.34	294	614.0	22.4
20	337	97.6	72.6	1.35	297	602.0	22.2
22	341	97.6	72.8	1.34	294	608.0	21.9
24	345	97.6	73.4	1.33	294	614.0	21.9

A comparative analysis of the forecast and actual indicators of the modes of operation of the plunger gas pumping unit (PGPU) under the conditions of the Bogorodchany UGS shows their satisfactory convergence. Thus, the performance of the compressor operation period in the process of injection according to the forecast deviates from the actual value for the whole period of operation of the PGPU in 2016 by 2.98%. The best match of fact and forecast is characteristic for August – 2.38%, and the greatest deviation is characteristic for October – 7.92%. The discrepancy between the predicted and actual power figures for the entire period of compressor injection is 9.81%. The smallest divergence in this indicator is characteristic for August and is 4.34%, and the largest – for October 19.43%.

CONCLUSIONS

The given indicators in comparison of the forecast and the fact testify to the adequacy of the method of forecasting the modes and maintenance of the PGPU in the conditions of the compressor station of underground gas storage and allow to recommend it for further implementation. The fuel gas consumption forecast for the compressor operation period deviates from the actual value by 2.51%. The smallest discrepancy between the forecast and actual results is characteristic for July and is 1.24%, the largest is observed in September and is 4.23%. random load of the system, which consists in the decision to translate the controlled system from its initial state to the final one by such a sequence of states that minimizes the overall in the evolution of the system.

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