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INFORMATION AND ANALYTICAL TECHNOLOGY FOR CONTROL AND OPERATION MANAGEMENT OF GAS TRANSPORTATION SYSTEMS OPERATION MODES

Andriy Tevyashev, Svitlana Iievlieva

Kharkiv National University of Radio Electronics, Nauka Ave, 14, Kharkov, 61000, Ukraine
andrew.teviashev@nure.ua, svitlana.iievlieva@nure.ua

Summary. The purpose of the study is to develop new information and analytical technologies and tools for optimal stochastic control of the technological processes of production, preparation, transportation and distribution of energy resources in the gas transportation systems of Ukraine.
The achievement of this goal will enable us to implement a unified, well-balanced approach to the modernization and rational development the gas transportation systems of Ukraine based on achieving maximum indicators in resource saving and environmentally friendly technologies in energy, which is currently extremely relevant.

Keywords: gas transportation systems, optimal stochastic control, information and analytical technologies

1. INFORMATION AND ANALYTICAL TECHNOLOGY OF OPERATIONAL DISPATCH CONTROL

The problem of optimizing the operational dispatch control (ODC) by the operation modes of gas transmission systems (GTS) has appeared since the moment of their creation and is becoming more urgent at the present time [4]. Modern GTS belong to the class of large technical systems and consist of an interconnected system of multi-line main gas pipelines with multi-station compressor stations (CS), multi-line linear sections with outlets that are connected by system bridges. In addition, the GTS also includes deposits and underground gas storage facilities (UGS), including well systems, gas gathering manifolds and booster compressor stations (BCS). The structure of the GTS can be linear, tree-like and / or annular. Multipurpose compressor stations are equipped with gas-pumping units (GPU) with an adjustable drive. To cool the gas at the outputs of all CS installed air-cooled (AC) with a regulated electric drive. Gas distribution stations (GDS) and natural gas consumers are connected to the outlets.

The emergence of a competitive natural gas market in Ukraine, the continuous increase in its cost, the natural aging of technological equipment, and the increasing intensity of its failures, have led to the need to manage not only the volumes and quality of gas supplied to consumers more quickly and efficiently, but also the directions of flows (up to the reverse) of transport gas in the GTS. Moreover, at the present day the problems of energy saving and environmental safety of the GTS have sharply escalated. All this led to the fact that the traditional methods of ODC lost their technological and economic efficiency [2, 4, 6]. The report considers one of the ways of systemic solution of the resource and energy saving problem in the GTS on the basis of the developed information and analytical technology (IAT) of the ODC.

The ITU ODC for a given time interval $[0,T]$ is an ordered sequence of solutions and realizations of the following problems:

- Operational forecasting (at zero time $t=0$ with anticipation *T*) of own production volumes and contracted volumes of supplies by all natural gas contractors in the GTS on the time interval $[0,T]$;
- Operational forecasting (at zero time $t=0$ with anticipation *T*) of natural gas consumption volumes by all categories of GTS consumers, depending on contract terms, chronological, meteorological and organizational factors;
- Calculation of the estimation of the dynamic balance of natural gas in the gas transportation system in the time interval $[0,T]$, estimation of the predicted operating conditions of each UGS (storage, injection, selection of natural gas) and the formation of boundary conditions for their work on the control interval $[0,T]$;
- Operational planning of quasi-stationary operating modes of BCS and UGS for a given time interval $[0,T]$;
- Operational planning of the quasi-stationary receiving mode, transporting and distributing the forecasted volumes of natural gas in the gas transportation system for a given time interval $[0,T]$;
- Operative receipt, processing and analysis of operational information, assessment of the actual state and operating mode of the GTS equipment for each time $\mathrm{t} \in [0,T]$;
- Adoption and implementation of decisions on the need to correct operational schedules of the operating mode of BCS and underground gas storage facilities and gas turbines for $\mathrm{t} \in [0,T]$;
- Adoption and implementation of decisions on the transfer of the operating mode of the gas transportation system from the actual at time $\mathrm{t} \in [0,T]$ to the planned quasi-stationary state;
- Stabilization of planned values of natural gas pressures and temperatures at the compressor station outputs for each time $\mathrm{t} \in [0,T]$.

Mathematical statements are given and algorithms for solving a number of ODC problem are considered in [2, 3, 5, 6].

The paper considers refined mathematical statements and methods for solving problems of the IAT ODC. Particular attention is paid to one of the most complex tasks of the ODC – the task of the operational planning transporting and distributing of natural gas in the gas transportation systems at a given time interval $[0,T]$.

2. MATHEMATICAL FORMULATION OF THE TASK OF THE OPERATIONAL PLANNING TRANSPORTING AND DISTRIBUTING OF NATURAL GAS IN THE GAS TRANSPORTATION SYSTEMS

2.1. THE GAS TRANSPORTATION SYSTEMS STRUCTURE MODEL

GTS structure is determined by its technological scheme, in which all open taps correspond to nodes between technological items, and closed-point gap between the technological elements. Changing the structure of the GTS by opening/closing cutting taps and is a function of the system interface. As a model for the structure of the GTS will use oriented linked graph $G(V,E)$ [6], which is supplemented with zero node and fictitious arcs connecting the zero node with all inputs and outputs of the GTS and inputs all active elements (AE), where V ($|V| = m$) – the set of nodes, E – the set of arcs ($|E| = n$). Choose a tree graph $G(V,E)$ so that its branches have become real and fictitious parts of the arc corresponding to the input of GTS. Then set of the graph arcs E is representable as a union of the following disjoint subsets: the real sections M; fictitious sections on the network inputs L; fictitious sections on the network output K; fictitious sections, connecting the input of the active elements with the zero node (fictitious additional network input) T; real tree branches M_1; real tree branches, which correspond to passive M_{11} and active M_{12} elements; real chords of the graph M_2; real chords of the graph which correspond to passive M_{21} and active M_{22} elements; fictitious branches of a tree, which correspond to inputs L_1; branches of a tree on the inputs of the network with a preset flow L_{11}, pressure L_{12} and temperature L_{13}; chords of the graph, which correspond to inputs L_2; chords of the graph of the network inputs with the preset flow L_{21}, pressure L_{22}, temperature L_{23}; fictitious chords which correspond to outputs K_2 $(K_2 = K)$; fictitious chords on the outputs of the network with a preset flow K_{21} pressure K_{22}, temperature K_{23}; fictitious chords of the graph, corresponding to fictitious additional network input (arcs connecting the input of the active elements with the zero point) with a preset flow T_{21}.

To construct stochastic models of technological elements of technological equipment quasi-stationary operating modes, we by introducing mathematical concept of a probability space, which has three components (Ω, B, P) – cartesian product of probability spaces (Ω_i, B_i, P_i), $i = 1, 2, ..., n$ ($\Omega = \Omega_1 \times \Omega_2 \times ... \times \Omega_n$, $B = B_1 \times B_2 \times ... \times B_n$, $P = P_1 \times P_2 \times ... \times P_n$, where Ω_i – space of elementary events; B_i – σ-algebras of Ω_i; P_i – probability measures on B_i).

Then $\forall \omega \in \Omega : X(\omega)$ – denotes a random value, while $P_i(\omega), q_j(\omega), T_i(\omega)$ – the random values characterizing the pressure and temperature of natural gas in the i-th node of the GTS and the flow at the j-th the section of the GTS; $\underset{\omega}{M}\{X(\omega)\}$ – the expected value $X(\omega)$.

2.2. THE STOCHASTIC MODEL OF QUASI-STATIONARY NON-ISOTHERMAL MODE OF TRANSPORT AND DISTRIBUTION OF NATURAL GAS IN THE GAS TRANSPORTATION SYSTEMS

Following [5] stochastic model of quasi-stationary non-isothermal mode of transport and distribution of natural gas in the GTS can be expressed as:

$$f_r = \underset{\omega}{M}\left\{\beta_r(\omega)q_r(\omega)^2 + \sum_{i\in M_{11}} b_{1ri}\beta_i(\omega)q_i(\omega)^2 + \sum_{i\in M_{12}} b_{1ri}\left\{\tilde{c}_i(\omega)\left(q_i(\omega) - \frac{\tilde{b}_i(\omega)P_{нi}(\omega)}{2\tilde{c}_i(\omega)}\right)^2 - \left(\tilde{a}_i(\omega) + \frac{\tilde{b}_i^2(\omega)}{4\tilde{c}_i(\omega)} - 1\right)P_{нi}(\omega)^2\right\}\right\} = 0, \qquad r \in M_{21}, \tag{1}$$

$$f_r = \underset{\omega}{M}\left\{\tilde{c}_r(\omega)\left(q_r(\omega) - \frac{\tilde{b}_r(\omega)P_{гн}(\omega)}{2\tilde{c}_r(\omega)}\right)^2 - \left(\tilde{a}_r(\omega) + \frac{\tilde{b}_r^2(\omega)}{4\tilde{c}_r(\omega)} - 1\right)P_{нг}(\omega)^2 + \sum_{i\in M_{11}} b_{1ri}\beta_i(\omega)q_i(\omega)^2 + \sum_{i\in M_{12}} b_{1ri}\left\{\tilde{c}_i(\omega)\left(q_i(\omega) - \frac{\tilde{b}_i(\omega)P_{нi}(\omega)}{2\tilde{c}_i(\omega)}\right)^2 - \left(\tilde{a}_i(\omega) + \frac{\tilde{b}_i^2(\omega)}{4\tilde{c}_i(\omega)} - 1\right)P_{нi}(\omega)^2\right\}\right\} = 0, \qquad r \in M_{22}, \tag{2}$$

$$f_r = \underset{\omega}{M}\left\{-P_{кг}(\omega)^2 - \sum_{i\in L_{11}} b_{1ri}P_{кi}(\omega)^2 - \sum_{i\in L_{12}} b_{1ri}P_{iк}^{+2} + \sum_{i\in M_{11}} b_{1ri}\beta_i(\omega)q_i(\omega)^2 + \sum_{i\in M_{12}} b_{1ri} \times \left\{\tilde{c}_i(\omega)\left(q_i(\omega) - \frac{\tilde{b}_i(\omega)P_{нi}(\omega)}{2\tilde{c}_i(\omega)}\right)^2 - \left(\tilde{a}_i(\omega) + \frac{\tilde{b}_i^2(\omega)}{4\tilde{c}_i(\omega)} - 1\right)P_{нi}(\omega)^2\right\}\right\} = 0, \qquad r \in L_{21}, \tag{3}$$

$$f_r = \underset{\omega}{M}\left\{-P_{кг}^{+2} - \sum_{i\in L_{11}} b_{1ri}P_{кi}(\omega)^2 - \sum_{i\in L_{12}} b_{1ri}P_{кi}^{+2} + \sum_{i\in M_{11}} b_{1ri}\beta_i(\omega)q_i(\omega)^2 + \sum_{i\in M_{12}} b_{1ri} \times \left\{\tilde{c}_i(\omega)\left(q_i(\omega) - \frac{\tilde{b}_i(\omega)P_{нi}(\omega)}{2\tilde{c}_i(\omega)}\right)^2 - \left(\tilde{a}_i(\omega) + \frac{\tilde{b}_i^2(\omega)}{4\tilde{c}_i(\omega)} - 1\right)P_{нi}(\omega)^2\right\}\right\} = 0, \qquad r \in L_{22}, \tag{4}$$

$$f_r = \underset{\omega}{M}\left\{P_{нr}(\omega)^2 - \sum_{i\in L_{11}} b_{1ri}P_{кi}(\omega)^2 - \sum_{i\in L_{12}} b_{1ri}P_{кi}^{+2} + \sum_{i\in M_{11}} b_{1ri}\beta_i(\omega)q_i(\omega)^2 + \right.$$
$$+\sum_{i\in M_{12}} b_{1ri}\left\{\tilde{c}_i(\omega)\left(q_i(\omega)-\frac{\tilde{b}_i(\omega)P_{нi}(\omega)}{2\tilde{c}_i(\omega)}\right)^2 - \right. \tag{5}$$
$$\left.\left. -\left(\tilde{a}_i(\omega)+\frac{\tilde{b}_i^2(\omega)}{4\tilde{c}_i(\omega)}-1\right)P_{нi}(\omega)^2\right\}\right\} = 0, \qquad r\in K_{21},$$

$$f_r = \underset{\omega}{M}\left\{P_{нr}^{+2} - \sum_{i\in L_{11}} b_{1ri}P_{кi}(\omega)^2 - \sum_{i\in L_{12}} b_{1ri}P_{кi}^{+2} + \sum_{i\in M_{11}} b_{1ri}\beta_i(\omega)q_i(\omega)^2 + \right.$$
$$+\sum_{i\in M_{12}} b_{1ri}\left\{\tilde{c}_i(\omega)\left(q_i(\omega)-\frac{\tilde{b}_i(\omega)P_{нi}(\omega)}{2\tilde{c}_i(\omega)}\right)^2 - \right. \tag{6}$$
$$\left.\left. -\left(\tilde{a}_i(\omega)+\frac{\tilde{b}_i^2(\omega)}{4\tilde{c}_i(\omega)}-1\right)P_{нi}(\omega)^2\right\}\right\} = 0, \qquad r\in K_{22},$$

$$f_r = \underset{\omega}{M}\left\{-P_{кr}(\omega)^2 - \sum_{i\in L_{11}} b_{1ri}P_{кi}(\omega)^2 - \sum_{i\in L_{12}} b_{1ri}P_{кi}^{+2} + \sum_{i\in M_{11}} b_{1ri}\beta_i(\omega)q_i(\omega)^2 + \right.$$
$$+\sum_{i\in M_{12}} b_{1ri}\left\{\tilde{c}_i(\omega)\left(q_i(\omega)-\frac{\tilde{b}_i(\omega)P_{нi}(\omega)}{2\tilde{c}_i(\omega)}\right)^2 - \right. \tag{7}$$
$$\left.\left. -\left(\tilde{a}_i(\omega)+\frac{\tilde{b}_i^2(\omega)}{4\tilde{c}_i(\omega)}-1\right)P_{нi}(\omega)^2\right\}\right\} = 0, \qquad r\in T_{21},$$

$$f_r = \underset{\omega}{M}\left\{\sum_{r\in M_2\cup L_{22}\cup K_{22}} b_{1ri}q_r(\omega) + \sum_{r\in L_{21}\cup K_{21}} b_{1ri}q_r^+ - q_i^+\right\} = 0, \tag{8}$$

$$f_r = \underset{\omega}{M}\left\{T_{кr}(\omega) - T_{гр} - \left(T_{нr}(\omega) - T_{гр}\right)e^{-\theta_r(\omega)L}\right\} = 0,\ r\in M_{11}\cup M_{21}\ , \tag{9}$$

$$f_r = \underset{\omega}{M}\left\{T_{кr}(\omega) - T_{нr}(\omega)\left(P_{кr}(\omega)/P_{нr}(\omega)\right)^{\frac{\mu_r(\omega)-1}{\mu_r(\omega)}}\right\} = 0,\ r\in M_{12}\cup M_{22}\ , \tag{10}$$

$$f_r = \underset{\omega}{M}\left\{T_{нr}(\omega)\sum_{i\in G_r^+} q_i(\omega) - \sum_{i\in G_r^-} q_i(\omega)T_{кi}(\omega)\right\} = 0,\ r\in V\ , \tag{11}$$

$$f_r = \underset{\omega}{M}\left\{n_k^r(\omega)\sum_{i\in G_r^-} q_i(\omega) - \sum_{i\in G_r^+} q_i(\omega)n_k^i(\omega)\right\} = 0, \quad k=1,2,...,m, \quad r\in V\ , \tag{12}$$

$$f_r = \underset{\omega}{M}\left\{T_{cpr}(\omega) - T_{гр}(\omega) + \left[(T_{нr}(\omega) - T_{гр}(\omega))/\theta_r(\omega)L\right](1 - e^{-\theta_r(\omega)L})\right\} = 0, \quad r \in M_{11} \cup M_{21} \qquad (13)$$

$$f_r = \underset{\omega}{M}\left\{P_{нr}^2(\omega) - P_{кr}^2(\omega) - \beta_r(\omega) q_r^2(\omega)\right\} = 0, \quad r \in M_{11} \cup M_{21} \qquad (14)$$

$$f_r = \underset{\omega}{M}\left\{\tilde{a}_r(\omega) P_{нr}^2(\omega) - P_{кr}^2(\omega) + \tilde{b}_r(\omega) P_{нr}(\omega) q_r(\omega) - \tilde{c}_r(\omega) q_r^2(\omega)\right\} = 0, \quad r \in M_{12} \cup M_{22} \qquad (15)$$

where:

$\overline{P}_{нi}^{+}, \overline{P}_{кi}^{+}, \overline{T}_{нi}^{+}, \overline{T}_{кi}^{+}, \overline{q}_r^{+}$ – marks the preset quantities, given by estimates of their mathematical expectations and variances $\sigma^2_{P^+_{нi}}, \sigma^2_{P^+_{кi}}, \sigma^2_{T^+_{нi}}, \sigma^2_{T^+_{кi}}, \sigma^2_{q^+_r}$;

G_i^+, G_i^- – the set of elements on which the gas comes into the i–th node, and is bled from it, respectively;

b_{1ri} – cyclomatic matrix element, located at the intersection of the r-th row and the i – th column;

$P_{нi}(\omega), P_{кi}(\omega)$; $T_{нi}(\omega), T_{кi}(\omega)$ – random variables, characterizing the pressure and the temperature at the beginning and the end of the i – th arc;

$q_i(\omega)$ – random variable characterizing the commercial flow of i – th arc;

$n_k^i(\omega)$ – estimation of the concentration of the k-th component of the natural gas in the incoming flow in r-th node of the GTS;

$n_k^r(\omega)$ – estimation of the concentration of the k-th component of the natural gas in the outcoming flow from r-th node of the GTS;

$\beta_i(\omega)$ – random variable characterizing the assessment ratio of hydraulic resistance of pipeline of i – th arc:

$$\beta_i(\omega) = \frac{\Delta(\omega) L T_{cp_i}(\omega) \cdot Z_{cp_i}(\omega)}{\tau_i \, \alpha_i^2 \phi_i^2 E_i^2(\omega) D_i^{5.2}} \qquad (16)$$

where $\Delta(\omega)$ – random variable characterizing the assessment ratio of the relative density of natural gas in the air, L – length i-th section of pipeline; $T_{cp_i}(\omega), Z_{cp_i}(\omega)$ – random variable characterizing the estimation of the average temperature and average density of natural gas of i-th arc, $E_i(\omega)$ – random variable characterizing the assessment of effectiveness ratio i-th section of pipeline, D_i – diameter i-th section of pipeline. In order to take into account the deviation of the gas flow mode from the quadratic effect appropriate correction factors are introduced α_i, ϕ_i, τ_i – numerical coefficients, the value of which depends on the selected units of measurement.

$\theta_i(\omega)L$ – Shukhov's criterion, random variable defined by the expression:

$$\theta_i(\omega)L = 62.6 K_{T_i}(\omega) D_{H_i} L / 10^6 q_i(\omega) \Delta(\omega) B(\omega) \qquad (17)$$

where $K_{T_i}(\omega)$ – random variable characterizing the estimate of the average values of the coefficient of heat transfer from the gas in the ground on the i - th section of the pipeline, $B(\omega)$– a random variable characterizing the estimate of the coefficient of the specific heat of natural gas, D_{H_i} – outside diameter i - th section of the pipeline.

$\tilde{a}_i(\omega), \tilde{b}_i(\omega), \tilde{c}_i(\omega)$ – $\tilde{a}_i(\omega), \tilde{b}_i(\omega), \tilde{c}_i(\omega)$ – random variable characterizing the approximation estimates for the coefficients describe the degree of compression of AE from the commercial flow for AE-owned i-th arc:

$$\tilde{a}_i(\omega) = a_{2i}(\omega), \qquad \tilde{b}_i(\omega) = b_{2i}(\omega)\frac{n}{n_0}\frac{\gamma_0 Z(\omega)RT_{нi}(\omega)}{1440} \tag{18}$$

$$\tilde{c}_i(\omega) = c_{2i}(\omega)\left(\frac{n}{n_0}\frac{\gamma_0 Z(\omega)RT_{нi}(\omega)}{1440}\right)^2$$

where:

$$\begin{aligned} a_{2i}(\omega) &= n'^4_i(\omega)\cdot a_{1i}(\omega) + 2n'^2_i(\omega)\left(1-n'^2_i(\omega)\right)a_{0i}(\omega) + \left(1-n'^2_i(\omega)\right)^2 \\ b_{2i}(\omega) &= n'^4_i(\omega)\cdot b_{1i}(\omega) + 2n'^2_i(\omega)\left(1-n'^2_i(\omega)\right)b_{0i}(\omega) \\ c_{2i}(\omega) &= n'^4_i(\omega)\cdot c_{1i}(\omega) + 2n'^2_i(\omega)\left(1-n'^2_i(\omega)\right)c_{0i}(\omega) \end{aligned} \tag{19}$$

where $a_{0i}(\omega), b_{0i}(\omega), c_{0i}(\omega)$ и $a_{1i}(\omega), b_{1i}(\omega), c_{1i}(\omega)$ – random variables characterizing the estimates of coefficients of approximation polynomials of the degree of compression AE first and second degree, respectively, at $\left(\frac{n}{n_0}\right)_{пр} = 1$;

$n'_i(\omega)$ – random variables characterizing the above assessment of the relative speed drive of i-th AE:

$$n'_i(\omega) = \left(\frac{n}{n_0}\right)_{iпр}(\omega) = \frac{n}{n_0}\sqrt{\frac{Z_{пр}(\omega)R_{пр}(\omega)T_{пр}(\omega)}{Z_н(\omega)\mathrm{R}_н(\omega)T_{нi}(\omega)}} \tag{20}$$

$$\mu'_i(\omega) = \frac{\mu_i(\omega)}{\mu_i(\omega)-1} = \eta_{пол\,i}(\omega)\frac{\mathrm{k}}{\mathrm{k}\text{-}1} \tag{21}$$

$\eta_{полi}(\omega)$ – random variable characterizing the assessment polytropic efficiency:

$$\eta_{полi}(\omega) = d_{0i}(\omega) + d_{1i}(\omega)Q_{прi}(\omega) + d_{2i}(\omega)Q^2_{прi}(\omega) + \mathrm{d}_{3\mathrm{i}}(\omega)Q^3_{прi}(\omega) \tag{22}$$

$Q_{прi}(\omega)$ – random variable characterizing the performance evaluation of the reduced volume of i-th AE.

$$Q_{прi}(\omega) = \frac{n_0}{n}\gamma_0\frac{Z(\omega)R(\omega)T_{нi}(\omega)}{1440}\frac{q_i(\omega)}{P_{нi}(\omega)} \tag{23}$$

The power consumed by the centrifugal supercharger (CBN) of AE, (kW) is estimated in accordance with the expression:

$$N_{ЦБН}(\omega) = N_i(\omega) / (0.95\eta_M) \quad (24)$$

where η_M (-) – is the mechanical efficiency CBN; $N_i(\omega)$ – power consumed by the CBN (kW), estimated by the formula:

$$N_i(\omega) = \frac{55.6 \cdot p_{вс}(\omega) \cdot Q(\omega)}{\eta_{пол}} \cdot \left(\varepsilon^{0.3}(\omega) - 1\right) \quad (25)$$

where $\varepsilon(\omega) = \dfrac{p_{наг}(\omega)}{p_{вс}(\omega)}$ – degree of pressure increase in the CBN (compression ratio); $\eta_{пол}$ – the polytropic efficiency of the CBN, in the absence of data, is assumed to be equal to 0.8.

The volumetric productivity of CBN Q (m^3/min.), Given the parameters of the natural gas at the inlet to the supercharger, is estimated by the formula:

$$Q(\omega) = \frac{0.24 \cdot Q_к(\omega) \cdot z_{вс}(\omega) \cdot T_{вс}(\omega)}{p_{вс}(\omega)} \quad (26)$$

where $Q_к(\omega)$ – commercial capacity of the centrifugal supercharger (million m^3/day) (at 293.15 K and 0.1013 MPa); $z_{вс}(\omega)$, $p_{вс}(\omega)$, $T_{вс}(\omega)$ – compressibility factor, absolute pressure (MPa) and temperature (K) of the natural gas at the entrance to the CBN.

The value of fuel gas consumption $q_{тг}(\omega)$ (thousand m^3/h) (at 293.15 K and 0.1013 MPa), for AE with gas turbine drive is estimated by the formula:

$$q_{тг}(\omega) = q_{тг}^{н} \cdot \left(0.76 \cdot \frac{N(\omega)}{N_e^{н}} + 0.25 \cdot \sqrt{\frac{T_з(\omega)}{T_з^{н}}} \cdot \frac{p_a}{0.1013}\right) \cdot \frac{Q_p^{н}}{Q_p(\omega)} \quad (27)$$

where $q_{тг}^{н}$ – nominal fuel gas flow rate, taking into account the correction for tolerances and technical condition; $N(\omega)$ – consumed power, obtained as a result of calculating the parameters of the supercharger; $Q_p(\omega)$ – combustion heat of fuel gas (kJ/m^3); $Q_p^{н}$ – the lowest heat of combustion of the fuel gas (kJ/m^3) (at 293.15 K and 0.1013 MPa) is taken equal to 34500 kJ/m^3. The value Q_p of the actual combustion heat of the fuel gas is estimated by the component composition of the transported gas at the input of the CBN.

Values $q_{тг}^{н}$, $N_e^{н}$, $T_з^{н}$, p_a, $T_з$ are evaluated according to the requirements of the norms [3].

The range of admissible modes (RAM) of the CBN AE operation is determined by the following system of inequalities:

- boundary of the surging zone CBN $Q_{\min}$ and maximum permissible volumetric capacity $Q_{\max}$:

$$Q_{\min} \leq Q_{np}(\omega) \leq Q_{\max} \tag{28}$$

- minimum – $n_{\min}$ and maximum – $n_{\max}$ drive speed of the CBN:

$$n_{\min} \leq n(\omega) \leq n_{\max} \tag{29}$$

- maximum (available) drive power:

$$N(\omega) \leq N_{pacn} \tag{30}$$

- the maximum outlet pressure determined by the ultimate strength of the pipes:

$$P_{\kappa i}(\omega) \leq P_{\text{мах}} \tag{31}$$

- maximum temperature of the gas at the outlet of the CBN, determined by the properties of the insulation coating:

$$T_{\kappa i}(\omega) < T_{\text{мах}} \tag{32}$$

The power consumed by the asynchronous electric motor of the fan drive air-cooling unit (ACU), N_{ABO} (kW) is found by the formula [1]:

$$N_{ABO}(\omega) = N_c(\omega) / \eta_э \tag{33}$$

where $\eta_э$ is the efficiency of the electric drive, and the power on the shaft depends on the relative speed of rotation of the fan in the third degree:

$$N_c(\omega) = N_{сном} \left(\frac{n(\omega)}{n_{ном}} \right)^3 \tag{34}$$

$n_{ном}$ – rated speed, $N_{сном}$ – rated power on the shaft of the fan ACU at rated speed.

The stochastic model of quasi-stationary non-isothermal mode of transport and distribution of natural gas in the gas transportation systems (1)–(15), taking into account equations (16)–(34), takes into account practically all the sources of internal and external uncertainty of the operation modes of the gas transportation system and allows to describe adequately the actual operating conditions of the GTS on the time interval $[0,T]$. This model is used to optimize the planned modes of operation of the GTS. At the same time, the optimal plan working of the gas transportation system in the time interval $[0,T]$ is represented in the form of the values of the mathematical expectations and variances in the parameters of the natural gas flows (pressures, flow, temperatures and composition of the natural gas) at all input and output of the gas turbine engine, mean and variances of the control parameters (speed of the drives). Calculation of the dispersion of the parameters of natural gas flows in the GTS is carried out by the method of stochastic linearization of the implicitly assigned functions of the deterministic equivalent of the stochastic model of quasi-stationary non-isothermal mode of transport and distribution of natural gas in the gas transportation systems.

3. MATHEMATICAL FORMULATION OF THE OPTIMIZATION PROBLEM OF THE STOCHASTIC MODEL OF QUASI-STATIONARY NON-ISOTHERMAL MODE OF TRANSPORT AND DISTRIBUTION OF NATURAL GAS IN THE GAS TRANSPORTATION SYSTEMS

The paper considers refined mathematical statements and methods for solving all problems of the IAT ODC [7, 8]. Particular attention is paid to one of the most complex tasks of ODC – the task of transport modes operational planning and distribution of natural gas in the gas transportation system for a given time interval $[0,T]$.

At the verbal level, this task is to select for such predicted volumes of supplies and consumption of natural gas in the GTS the operating modes of BCS, UGS and CS in the time interval $[0,T]$ at which:

- all GTS consumers will be provided with the necessary (predicted) volumes of natural gas;
- the probability that the value of each constituent of the natural gas composition, including its calorific value, is less than its limit value should be less than a predetermined small value (close to zero);
- the probability of technological restrictions violation on pressure, flow, power and temperature of natural gas on all elements of the process equipment should be less than a predetermined small value (close to zero);
- the probability that the mathematical expectation of the total gas supply in the gas turbine system will be greater or equal to some forward value of the given guaranteed value will be close to unity;
- the mathematical expectation of total power inputs by all gas compressor units and ACU operating on the time interval $[0,T]$ should be minimal;
- the likelihood of finding work points of technological equipment in the area of their admissible modes, will be close to unity.

This makes it possible to obtain not only the optimal plan for the operation of the GTS for a given time interval $[0,T]$, but also a plan that has regime stability to the predicted level of stochastic disturbances throughout the control interval $[0,T]$.

3.1. MATHEMATICAL FORMULATION OF THE PROBLEM

For the statement of the problem, let's $N_{i_t}^{j_k}\left(q_{i_t}^{j_k}(\omega), \varepsilon_i^{j_k}(\omega)\right)$ – power consumed by the *k*-th AE, and $N_t^j\left(q_t^{jk}(\omega), T_{oc}^0(\omega), \Delta T^0\right)$ – the electric energy consumption of the consumed ACU on the *j*-й КС th CS at time *t*.

Then the problem of optimizing the planned modes of transport and distribution of natural gas in the GTS will be considered as a problem of non-linear stochastic programming (NSP) with statistical and probabilistic constraints – it is necessary to find the minimum of the mathematical expectation of the total consumed power CBN and the energy consumed by all ABO, working at all CS GTS on the time interval $[0,T]$ in the range of constraints Ω.

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$$\underset{\omega}{M}\sum_{t=0}^{T}\sum_{j=1}^{N}\sum_{k=1}^{L}\Big[N_t^{jk}\left(q_t^{jk}(\omega),\varepsilon_t^{jk}(\omega)\right)+N_t^{j}\left(q_t^{jk}(\omega),T_{oc}^{0}(\omega),\Delta T^{0}\right)\Big]\to\min_{u_t\to\Omega} \quad (35)$$

The range of constraints for problem (35) Ω is determined by the system of equations of the stochastic model of transport and distribution of natural gas in the GTS (1)–(15), taking into account stochastic equations (16)–(34) and probabilistic constraints of the form:

$$P(P_i(\omega)\le P_i^{\min})\le\alpha,\ \ \textit{где}\ \ \alpha\approx 0,\ \ i\in V \quad (36)$$

$$P(P_i(\omega)\ge P_i^{\max})\le\alpha,\ \ \textit{где}\ \ \alpha\approx 0,\ \ i\in V \quad (37)$$

$$P(Q_{k\ np}(\omega)\le Q_{k\ np}^{\min})\le\alpha,\ \ \textit{где}\ \ \alpha\approx 0,\ \ \forall k \quad (38)$$

$$P(Q_{k\ np}(\omega)\ge Q_{k\ np}^{\max})\le\alpha,\ \ \textit{где}\ \ \alpha\approx 0,\ \ \forall k \quad (39)$$

$$P(T_k(\omega)\le T_k^{\min})\le\alpha,\ \ \textit{где}\ \ \alpha\approx 0,\ \ \forall k \quad (40)$$

$$P(T_k(\omega)\ge T_k^{\max})\le\alpha,\ \ \textit{где}\ \ \alpha\approx 0,\ \ \forall k \quad (41)$$

$$P(Q_{зг}(\omega)\le Q_{зг}^{\min})\le\alpha,\ \ \textit{где}\ \ \alpha\approx 0, \quad (42)$$

$$P(\mathrm{TS}_r(\omega)\le TS_0)\le\alpha,\ \ \textit{где}\ \ \alpha\approx 0. \quad (43)$$

$$P((\varepsilon_i(\omega),Q_{npi}(\omega),N_i(\omega))\in RAM)\ge\beta,\ \ \textit{где}\ \ \beta\approx 1. \quad (44)$$

Where $Q_{зг}(\omega)$ – the gas reserve in the GTS (million m^3), – the calorific value of natural gas in the r-th node of GTS; TS_0 – the nominal heating value of natural gas. Equation (44) indicates that the operating point of each AE should belong to the RAM of the work of the CBN.

To construct the deterministic equivalent of the objective function (35), constraints (1)–(15) and equations (16)–(34), we replace all the random variables included in them, with estimates of their mathematical expectations. Because of the nonlinearity of the equations, such a replacement leads to the appearance of non-zero residuals on the right-hand side of the equation, the sign and magnitude of which, in accordance with the Jensen inequality [2], is determined by the degree of convexity (concavity) of the implicit functions of the corresponding variables. As shown by the studies carried out [3], the numerical value of these residuals is comparable to the error value in the numerical solution of the system of equations of the deterministic equivalent (1)–(15). Therefore, without loss of accuracy, the discrepancies in the deterministic equivalent of the objective function (35), the statistical constraints (1)–(15) and the constraint equations (16)–(34) will be neglected. The construction of the deterministic equivalent of the probability constraints (36)–(44) under the known (normal) law and parameters (mathematical expectation and variance) of the distribution of random variables is performed by the standard method.

In [10], the strategy of the optimization problem of the stochastic model of quasi-stationary non-isothermal mode of transport and distribution of natural gas in the gas transportation systems was selected and justified. The essence of this strategy is as follows: in order to maximize the mathematical expectation of the gas reserve in the GTS and minimize the mathematical expectation of the total power consumed by the all CBN and the power consumed by the all asynchronous electric motor on all CS, it is necessary to maximize the pressure and minimize the NG temperature at the output of each CS (at each inlet of the pipeline linear section (LS)) of multipurpose CS to the maximum permissible values. This strategy does not guarantee an optimal solution, but the rational solutions obtained with the help of this strategy proved to be very effective.

3.2. ESTIMATION OF ECONOMIC EFFICIENCY OF THE PROPOSED OPTIMIZATION STRATEGY FOR QUASI-STATIONARY OPERATION MODES OF THE GAS TRANSPORTATION SYSTEMS

Estimation of economic efficiency of the proposed optimization strategy for quasi-stationary operating modes of the gas transportation systems was carried out for a 1209 km long magistral gas pipeline (MG) consisting of 10 consecutive linear sections, between which there are 9 CSs (Table 1):

Table 1. Structure of the of the MG

No.	Name of section GP	Length of section MG (km)	Pipe diameter (mm) / wall thickness (mm)
1.	Input - CS 1	122.00	1420/16.5
2.	CS 1 - CS 2	101.00	1420/16.5
3.	CS 2 - CS 3	126.00	1420/16.5
4.	CS 3 - CS 4	130.50	1420/16.5
5.	CS 4 - CS 5	108.50	1420/16.5
6.	CS 5 - CS 6	121.10	1420/16.5
7.	CS 6 - CS 7	119.90	1420/16.5
8.	CS 7 - CS 8	121.00	1420/16.5
9.	CS 8 - CS 9	123.00	1420/16.5
10.	CS 9 - Output	136.20	1420/16.5

The initial data on the component composition. as well as the error in the results of measurements of the molar proportions of the component composition (according to [3]) are given in Table 2.

Table 2. Initial data on the component composition of natural gas

Name of component	Estimate of mean molar. fraction $\overline{x}_i$	Molar mass. M_i (kg/kmol)	Uncertainty of measurement results (%)	Density $\rho_{c.u}$ (kg/m^3)
Methane	0.8927	16.043	0.210651	0.66692
Ethane	0.0226	30.07	0.09066	1.25004
Propane	0.0106	44.097	0.06384	1.83315
i-butane	0.0001	58.123	0.00084	2.41623
Nitrogen	0.0004	28.135	0.0029	1.16455
Dioxide	0.043	44.01	0.2592	1.82954
Hydrogen sulfide	0.0305	34.082	0.18324	1.41682
Propylene	0.0001	42.081	0.00084	1.74935
Total	1			

For this MG's configuration two operating modes of the CS are considered. For each mode. the initial pressure and temperature in the first section were assumed to be 7.1 MPa and 301.2 (K). respectively. Commercial gas consumption $q = 76{,}2\,\text{mln.m}^3/\text{day}$.

The pressure distribution along the MG. at a constant ε = 1.25 of the compression ratio of the SG on all the CS is shown in Fig. 1.

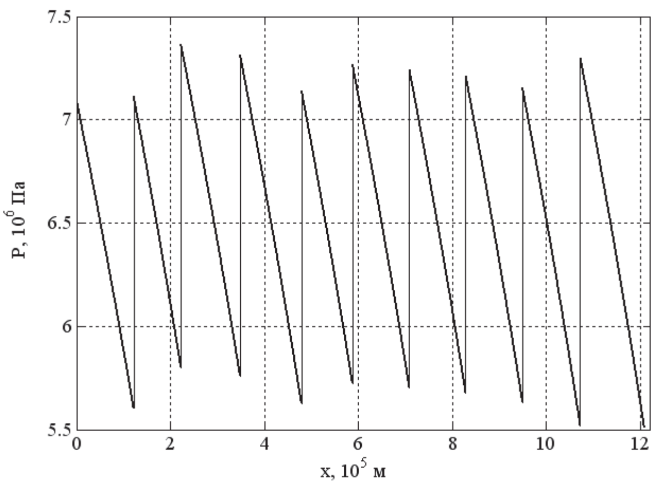

Fig. 1. The pressure distribution along the MG at a constant ε = 1.25

The results of calculations of the quasi-stationary non-isothermal regime of natural gas transport at the input and output of each CS are shown in Table 3.

Table 3. Results of calculating for quasi-stationary operating modes of the gas transportation systems at a constant ε = 1.25

№ CS	$P_{нi}$ (MPa)	$P_{кi}$ (MPa)	$T_{нi}$ (K)	$T_{кi}$ (K)	$q_{тг}$ (mln.m^3/day)	q_i (mln.m^3/day)
1	5.603	7.1159	292.6914	311	0.25802	76.195
2	5.7975	7.3628	298.04	311	0.26179	76.036
3	5.7566	7.3109	295.6	311	0.25857	75.777
4	5.6236	7.1419	295.11	311	0.25816	75.519
5	5.7227	7.2678	297.25	311	0.25902	75.26
6	5.703	7.2428	296.02	311	0.25701	75.003
7	5.6789	7.2123	296.96	311	0.2574	74.746
8	5.6321	7.1528	295.99	311	0.25588	74.49
9	5.5188	7.3	296.23	311	0.2932	74.197

In the second case, the pressure at each CS was raised to the maximum allowable value of 7.8 MPa (according to the optimization strategy for quasi-stationary non-isothermal transport modes and the distribution of NG in the GTS). Note that the maximum possible pressure at the output of the CPU is 8 MPa. However, taking into account the deterministic analogues (31)–(39), the value of the pressure stabilization dispersion at the output of the CS is obtained. Using the "three sigma" rule, we get that the maximum permissible pressure at the output of the compressor is 7.8 MPa. Results of calculations and the values of the variances for the obtained mode of natural gas transport by MG at the maximum permissible pressure at the output of the CS are shown in Fig. 2 and in Table 4.

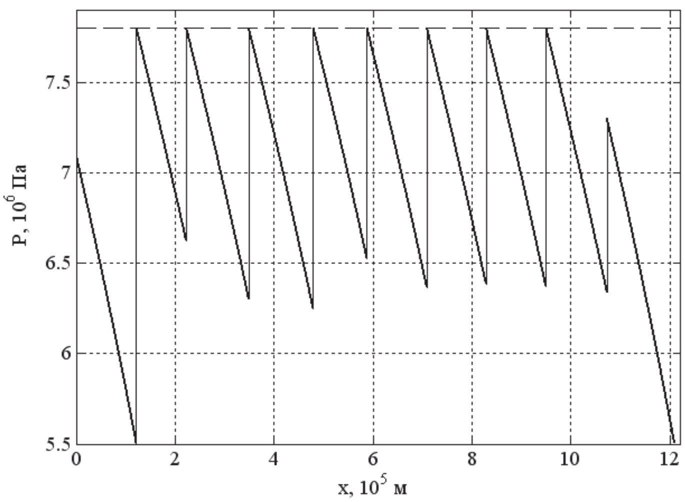

Fig. 2. Distribution of pressure along the MG at the maximum permissible pressure at the output of the CS

Table 4. Results of calculations and the values of the variances for the obtained mode of natural gas transport by MG at the maximum permissible pressure at the output of the CS

№	$P_{нi}$ (MPa)	$D_{P_{нi}}$	$P_{кi}$ (MPa)	$D_{P_{кi}}$	$T_{кi}$ (K)	$D_{T_{кi}}$	q_i (mln.m^3/day)	D_{q_i}
1	7.192	0.0003	5.603	0.031	292.692	0.232	76.195	13.821
2	7.800	0.0003	6.599	0.015	296.106	0.309	76.195	13.411
3	7.800	0.0003	6.281	0.025	298.282	0.364	76.036	12.748
4	7.800	0.0003	6.234	0.026	298.669	0.366	75.777	12.314
5	7.800	0.0003	6.528	0.016	296.874	0.306	75.519	11.905
6	7.800	0.0003	6.379	0.020	297.987	0.327	75.260	11.318
7	7.800	0.0003	6.405	0.018	297.922	0.316	75.003	10.840
8	7.800	0.0003	6.402	0.017	298.047	0.309	74.746	10.350
9	7.800	0.0003	6.388	0.017	298.246	0.305	74.490	9.865
10	7.800	0.0003	6.235	0.021	299.318	0.321	74.197	9.392

In the first case. the total power consumed by the gas compressor unit. N = 2.7357·105 kW. in the second case N = 2.3361·105 kW. Thus. increasing the pressure at the compressor station to the maximum possible leads to a decrease in the pressure drop in the next section after it. which in total allows reducing the consumed power consumption of the gas compressor unit by 14.6%.

Total fuel gas costs for all compressor stations for the first mode amounted to 2.3588 million m^3/day. and for the second mode – 2.1088 million m^3/day. Thus. increasing the pressure at the compressor station to the maximum allowable allows reducing the total consumption of fuel gas for gas turbine plants by 10.6%.

4. CONCLUSIONS

The proposed model and optimization strategy for quasi-stationary operating modes of gas transmission systems is an effective tool for solving the multicriteria task of operational scheduling of GTS operation modes based on the use of the specific features of natural gas transport along linear sections of main gas pipelines and its compression at compressor stations that significantly expand the agreement area of the multicriteria problem and significantly increase all technical and economic indicators planned regimes.

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INFORMACJA I TECHNOLOGIA ANALITYCZNA DO ZARZĄDZANIA TRYBEM PRACY PRZY KONTROLI I OBSŁUDZE SYSTEMÓW TRASPORTOWYCH GAZU

Streszczenie

Celem badań jest opracowanie nowych technologii narzędzi informacyjnych i analitycznych dla optymalnego stochastycznego sterowania procesami technolo–gicznymi produkcji, przygotowania, transportu i dystrybucji surowców energe–tycznych w systemach transportu gazu na Ukrainie.

słowa kluczowe: systemy transportu gazu, optymalna kontrola stochastyczna, technologie informacyjne i analityczne