Information and Analytical Technology for Control and Operation Management of Gas Transportation Systems Operation Modes

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***Abstract*–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.

I. 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 [1]. 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 [1,2,3]. 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 t [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 t [0, T];

- Adoption and implementation of decisions on the transfer of the operating mode of the gas transportation system from the actual at time t [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 t [0, T].

Mathematical statements are given and algorithms for solving a number of ODC problem are considered in [2,3,4].

II. Mathematical Formulation of The Task of The Operational Planning Transporting and Distributing of Natural Gas in The Gas Transportation Systems

A. 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 $G(V,E)$ [2], 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 $X(\omega)$.

B. 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:

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

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

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

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

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

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

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

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

$$f_r = \underset{\omega}{M}\left\{T_{\kappa r}(\omega) - T_{\textit{г}p} - \left(T_{\textit{н}r}(\omega) - T_{\textit{г}p}\right)e^{-\theta_r(\omega)L}\right\} = 0\,, \ r \in M_{11} \cup M_{21}\ ; \tag{9}$$

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

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

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

$$f_r = \underset{\omega}{M}\left\{T_{cpr}(\omega) - T_{\textit{г}p}(\omega) + \left[(T_{\textit{н}r}(\omega) - T_{\textit{г}p}(\omega))/\theta_r(\omega)L\right](1 - e^{-\theta_r(\omega)L})\right\} = 0\ , r \in M_{11} \cup M_{21}\ ; \tag{13}$$

$$f_r = \underset{\omega}{M}\left\{P_{\textit{н}r}^2(\omega) - P_{\kappa r}^2(\omega) - \beta_r(\omega)q_r^2(\omega)\right\} = 0\,, \ r \in M_{11} \cup M_{21}\ ; \tag{14}$$

$$f_r = \underset{\omega}{M}\left\{\tilde{a}_r(\omega)P_{\textit{н}r}^2(\omega) - P_{\kappa r}^2(\omega) + \tilde{b}_r(\omega)P_{\textit{н}r}(\omega)q_r(\omega) - \tilde{c}_r(\omega)q_r^2(\omega)\right\} = 0\,, \ r \in M_{12} \cup M_{22}\ . \tag{15}$$

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;

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

$n^r_k(\omega)$ – 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:

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

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:

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

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.

$\tilde{a}_i(\omega), \tilde{b}_i(\omega), \tilde{c}_i(\omega)$ – 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:

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

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

where:

$$a_{2i}(\omega) = n'^4_i(\omega) \cdot a_{1i}(\omega) + 2n'^2_i(\omega)\left(1 - n'^2_i(\omega)\right) a_{0i}(\omega) + \\ + \left(1 - n'^2_i(\omega)\right)^2 ,$$

$$b_{2i}(\omega) = n'^4_i(\omega) \cdot b_{1i}(\omega) + 2n'^2_i(\omega)\left(1 - n'^2_i(\omega)\right) b_{0i}(\omega) ,$$

$$c_{2i}(\omega) = n'^4_i(\omega) \cdot c_{1i}(\omega) + 2n'^2_i(\omega)\left(1 - n'^2_i(\omega)\right) c_{0i}(\omega) ,$$

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 $\left(\frac{n}{n_0}\right)_{np} = 1$.

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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