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Control of gas transmission system in non-stationary consumption modes

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Abstract. The article deals with the issues of modeling and control of the gas transmission system in non-stationary consumption modes. The topology of the gas transmission network is parameterized in the form of a digraph, with weighted vertices representing the vertices-the drains of consumers, the vertices-the sources of suppliers, transit vertices (compressor or gas distribution stations) and arcs indicating the main parameters that affect the throughput of the system. A hierarchical model of gas transportation system management is proposed, where the upper level is the flow diagram of gas transport, and the lower level simulates the physical processes of gas flow in the pipe section. A procedure for dynamic control in non-stationary consumption modes is developed, which is represented as a sequence of transitions between stationary flow schemes according to the criterion of minimizing their mismatch at neighboring time intervals corresponding to the intervals of constancy of consumption requests, which further reduces the energy costs of changing the flow scheme. The practical value of the research results lies in the possibility of their use while dispatching control.

1. Introduction

The main task of the gas transmission management system is to ensure uninterrupted gas supply to consumers [1]. In general, the system consists of two parts: a dispatching control and management system operating in real time and a dispatching decision support system [2]. Modern dispatch control systems are built on the basis of business process models based on the modular principle, have a flexible architecture and provide management in distributed and multi-level systems, depending on the results of situational analysis of the technological process [3]. The system provides a comprehensive and “end-to-end” solution to the tasks of planning, operational management and commercial management of the work of an enterprise or company [4]. For the gas distribution system of an industrial cluster, the most “rigid” restriction is the unconditional fulfillment of planned gas supplies to consumers with the elimination of identified deviations in the process of operational dispatching control [5]. At the same time, the complexity of controlling the gas transmission system (GTS) is justified by its large inertia, as well as restrictions on [6]:

- available gas supply in pipelines;
- maximum and minimum pressure;
- maximum pressure change rate;

- for the maximum throughput capacity of the pipe section (PS).

It should be noted that currently insufficient attention is paid to the description of non-stationary modes of functioning of the GTS, when consumer requests may change during the day. This paper is devoted to modeling and optimization of GTS control in non-stationary gas consumption modes. The novelty of the research lies in the formal representation of the GTS in the form of a two-level scheme of nested models, which is reduced to the formalism of a hybrid automaton. At the same time, the mutual parameterization of the upper and lower level models forms the balance equations, and the dynamics of functioning is represented by a simulation scheme. In addition, a model for controlling non-stationary modes is proposed in the form of a sequence of stationary flow diagrams, the calculation of which is performed on the basis of the criterion for minimizing their mismatch.

2. Research methods

Analytical and statistical research methods [4,7,8] have shown that transient processes propagate along the length of the gas pipeline very slowly. So, for a gas pipeline with a length of 700 km, the head wave of the change reaches a value equal to 0.85 from a single jump in 7...10 hours, and the entire gas pipeline will switch to a new stationary mode after three days. Such features of the technological processes of gas production and transmission impose serious restrictions on the control systems of this process, giving each automated process control system (APCS) both common to a particular process and specific features inherent only to it. Already during the day [9-11], the requested volumes of gas from large consumers can be cyclically repeated, including due to the adjustment of planned indicators. For planning the GTS mode and drawing up a switching plan, non-stationary mathematical models of the GTS in the mode of variant calculations are currently actively used, where the current on-line mode is taken as the initial state. This is determined by the fact that there is a significant daily and daytime unevenness of gas consumption, and the available resources (gas supply in the pipeline, Gas pumping units (GPU) capacity reserves and gas supply) are limited.

Mathematical models of non-stationary non-isothermal flow processes in pipes are well known, and simulation with their help of modes for systems that are simple in configuration is technically quite feasible [12]. Fundamental difficulties will appear when trying to create and implement a method for determining optimal non-stationary modes for complex large-scale systems [1,13,14].

As a result of the analysis of GTS control models in non-stationary modes, the paper proposes the integration of these models together with models of physical processes, methods for calculating flow diagrams, as well as control models into a discrete-event analytical-simulation model with a two-level hierarchical structure and their mutual parameterization. The upper level is a weighted digraph of the GTS. In the GTS topology description model, vertices represent such GTS objects as wells (W), underground gas storage facilities (UGSF), compressor stations (CS), gas distribution stations (GDS), main gas pipeline (MG), pipe sections (PS). The main tasks of the top level are the description of flow diagrams for various states of the GTS. The lower level is a set of models of physical processes of gas flow in a pipe, which are represented by a system of differential equations. The calculation results are the functions of pressure, velocity, commercial gas flow and other characteristics for the entire section of the gas pipeline.

With this formulation, the paper suggests combining these two processes in the form of a scheme of nested descriptions, that is, the calculation of the upper-level model sets the parameters of the gas flow in the lower-level models. In turn, the calculation of the characteristics of gas flows implements the parameterization of the upper-level model, since the recalculation can change the throughput of each PS. As an implementation of this combined discrete-continuous process (discrete control actions of the upper-level model together with the implementation of continuous dynamic models of state changes of all PS, it is proposed to use the formalization of a hybrid automaton.

The upper level of the GTS control model is a weighted digraph $G_r = (G, E)$ with many vertices $G = \{G_i\}, i = 1, \dots, |G|$ and a lot of arcs $E = \{E_{ij}\}, i, j = 1, \dots, |G|$ or in a single-index representation, which is more convenient for the incident matrix $E = \{E_i\}, i = 1, \dots, |E|$. The set of vertices is a union of sets $G = G^s \cup G^f \cup G^c$, where G^s - vertices -sources (weighted by the time series of gas supplies); G^f –

vertices-drains (weighted by the time series of the consumption forecast); G^c – transit vertices (weighted by the energy capabilities of the corresponding compressor stations). Arches E_{ij} correspond PS, which are weighted by the length parameters $L = \|l_{ij}\|$, и $D = \|d_{ij}\|$. Using the work of Hadamard «$\odot$», the volumes of PS are also reduced to a matrix $V = L \odot D, V = \|v_{ij}\|$, where v_{ij} – volume of PS E_{ij} . For the various types of GTS there are restrictions on pressures p_{min} and p_{max} , what determines the minimum $M^{min} = \|M_{ij}^{min}\|$ and the maximum $M^{max} = \|M_{ij}^{max}\|$ of gas masses in all arcs E_{ij}, of the corresponding PS.

In the current practice, each consumer $G_i \in G^f$ makes requests for gas supplies with a sampling of 1 hour. But, as a rule, these requests are almost always adjusted depending on weather conditions, so the work solves the problem of forecasting the volume of deliveries to consumers, which forms the time series $M_{out_i}(t)$. For suppliers, the time series is usually degenerate and is determined by a constant volume of deliveries, however, for possible extensions of the boundaries of using the developed model, we assume that for each supplier $G_i \in G^s$, a time series $M_{in_i}(t)$ with a discretization of 1 hour is also given. For transit vertices $G_i \in G^c$ we will assume the equality of flows at the input and output, and the parameters are the maximum performance for evaluating the throughput of flow diagrams.

The listed time series are combined into a single multidimensional series of nodal expenses $Q(t) = (Q_1(t), = (Q_1(t), \dots, = (Q_{|G|}(t))$, and at each moment of time for $G_i \in G^s, M_{in_i}(t) = Q_i \geq 0$, for $G_i \in G^f, M_{out_i}(t) = Q_i \leq 0$ and for $G_i \in G^c, Q_i = 0$.

The state of the model at each moment of time t the combination of the masses of all PS is calculated $M(t) = \|M_{ij}(t)\|, i, j = 1, \dots, N$, that is, the residual mass of the gas in all PS, subject to the restrictions $M_{ij}^{min} \leq M_{ij}(t) \leq M_{ij}^{max}$.

For modeling the functioning process, the discretization of the recalculation time of the model states can be arbitrary, but for interpreting the results, the clock cycle is defined as 0.1 hours. For the selected sampling time Δt, based on the existing bandwidth limitations, restrictions on the sampling and gas injection at each clock cycle are formed.

For feasibility in a software modeling complex, lower-level models can be represented as: systems of differential equations with an indication of the numerical methods used to solve them; systems of algebraic equations under conditions of equality of the number of variables and the number of equations, as well as its definiteness; a set of analytical expressions that correspond to the solution of the corresponding systems of algebraic or differential equations [15].

The given models of the physical processes of gas flow in the PS are adapted to linear and nonlinear interface models of restrictions on the injection $\Delta M_{ij}^{in}(t)$ and the selection $\Delta M_{ij}^{out}(t)$ of gas in the PS E_{ij} at the moment t, reduced to the scale of one clock cycle of the model time. In general, these restrictions depend on the residual mass and the pressure function over the entire pipe section. For a linear model, it is assumed in this paper that these restrictions depend only on the current residual mass (the state of the model), i.e. $\Delta M_{ij}^{in}(t)=\Delta M_{ij}^{in}(M_{ij}(t))$ и $\Delta M_{ij}^{out}(t)=\Delta M_{ij}^{out}\left(M_{ij}(t)\right)$, and linearly:

$$\Delta M_{ij}^{in}(t)=a^{in} + b^{in} * M_{ij}(t), \ \Delta M_{ij}^{out}(t)=a^{out} + b^{out} * M_{ij}(t) \tag{1}$$

Model parameters a^{in}, b^{in} and a^{out}, b^{out} a^{out} and b^{out}· are calculated on the basis of the given physical models.

The nonlinear model of gas injection/selection constraints is based on the approximation of the results of calculating pressure functions throughout each PS by the Laguerre function system [16] according to the physical models included in the modeling system.

Schemes for converting pressure functions into gas injection/selection restrictions based on limiting the gas velocity at a given pressure, when the residual mass $M_{ij}(t)$ of PS is given, are proposed. The schemes for injection, selection (figure 1) and the simultaneous injection/selection process, where G^* corresponds to the selected gas volume, are considered separately.

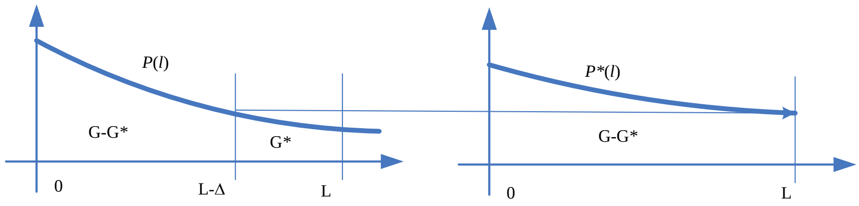
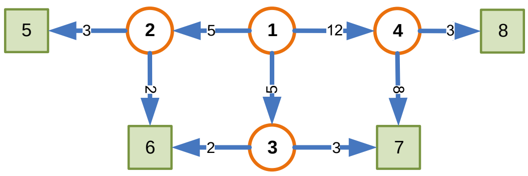


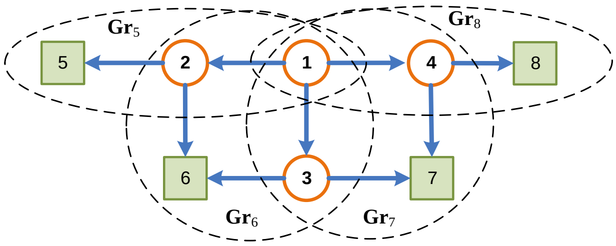
Figure 1. Nonlinear model of gas selection

Let M be the residual mass in and out of the PS for a given pressure distribution $P(l)$ the mass is selected $M^*=\int_{L-\Delta}^{L} P(l)dl = \frac{-p_0}{c} e^{-cL} = \frac{-p_0}{c}\left(e^{-cL} + e^{-c(L-\Delta)}\right)$ and Δ it is determined from this equation based on the ratio $\Delta = L + \frac{1}{c} ln\left(\frac{M^* c}{p_0} + e^{-cL}\right)$. For the general case of the Laguerre polynomial, the inverse equation is solved. It is assumed that the value of the transformed function P^* at the end of interval $P^*(L)$=$P(L$-Δ$)$, i.e. $P^*(L) = p_0 e^{-c(L-\Delta)} = P^k$. It is also assumed that the total mass remains $M - M^*$, so $\int_0^{L-\Delta} P(l)dl = \int_0^L P*(l)dl$, which leads to the solution of a system of equations for finding new values p^*_0 and c^*. Similarly, models of injection and simultaneous injection/selection process are constructed.

The control at each moment of the model time is an arbitrary flow diagram $F = (q_1, q_2, \dots, q_{|E|})$, and the control process in the simulation model is set as a sequence of flow diagrams $F^{(1)}, F^{(2)}, \dots, F^{(K)}$, which is chosen from any considerations of optimizing the process of functioning of the GTS (figure 2).



a) flow control diagram



b) consumer supply subnetworks

Figure 2. Flow diagrams of gas transport

The main task of the control is to form a sequence of flow diagrams according to the selected optimality criterion. Naturally, the diagrams F^k are formed in some accordance with the node costs $Q(t) = (Q_1(t), = (Q_1(t), \dots, = (Q_{|G|}(t))$, at a given time interval. Node costs are modeled in accordance with the specified time series of deliveries (t) $(Q_i(t) > 0, G_i \in G^s)$ and consumption forecast $(Q_i(t) < 0, G_i \in G^f)$, and in all transit vertices, the node costs are zero $(Q_i(t) = 0, G_i \in G^c)$.

To implement the flow control diagram, an algorithm for changing states is proposed:

- calculation of injection restrictions ΔM_i^{in} and selection ΔM_{ij}^{out} for all PS according to the formulas (1);
- in case $M_i^{in} < \Delta M_i^{in}$, then $\Delta Mf_i^{in} = M_i^{in}$, in case $M^{in}(q_i) > \Delta M_i^{in}$, then $\Delta Mf_i^{in} = \Delta M_i^{in}$;

• in case $M^{out}(q_i) < \Delta M_i^{out}$, then $\Delta Mf_i^{out} = M^{out}(q_i)$, in case $M^{out}(q_i) > \Delta M_i^{out}$, then $\Delta Mf_i^{out} = \Delta M_i^{out}$.

All calculated masses for injection and selection are combined into matrices $\Delta M^{+}(t)$ and $\Delta M^{-}(t)$, accordingly. As a result, a new state matrix is formed at the next moment of the model time $(t+1) = M(t) + \Delta M^{+}(t) - \Delta M^{-}(t)$. In addition, depending on the set controls in the form of flow diagrams at time intervals (corresponding to the intervals of constancy of supply and consumption volumes), the developed model allows to obtain time series of discrepancies between planned and actual volumes for each consumer. In the presence of a non-stationary consumption mode and possible imbalances with gas supplies, these flow diagrams calculation models are used to search for rational control actions. The control is a change in the network topology due to the choice of switching cranes, jumpers, etc., as well as a change in pressure on linear sections due to the choice of operating modes aimed at selecting pressure, but without taking into account the own gas consumption and modeling the physical processes occurring in the CS itself.

The main criterion is the additive convolution of under-deliveries and gas surpluses for all consumers and for the entire planning horizon $F(T) = \sum_{t=1}^{T} \sum_{i \in G} w_i^{-} \left(IS_t^i \dot{-} ISR_t^i\right) + \sum_{t=1}^{T} \sum_{i \in G^{CT}} w_i^{+} \left(ISR_t^i \dot{-} IS_t^i\right)$ где IS_t^i, - time series of requests for deliveries; ISR_t^i - time series of actual deliveries; w_i^{-}, w_i^{+} - weighting factors for under-deliveries and exceeding the required volumes; $a \dot{-} b$ - truncated subtraction operation. However, within the framework of solving the general optimization problem, it is possible to parameterize the model with various management strategies. These include the strategy of maintaining the maximum gas supply in the system, the strategy of minimizing energy consumption in the absence of a shortage, minimizing gas shortage, and other strategies. The control actions are largely determined by the total gas reserves in all PS of the GTS and the possible gas reserve for each consumer.

The total reserve stock is defined as the sum of all the maximum PS masses $M^{max} = \sum_{i,j} M_{ij}^{max}$. Possible reserve for the consumer G_i is determined based on the formation of a supply subnetwork Gr_i (figure **Error! Reference source not found.**), which represents the set of all PS from which it is possible to supply gas to the consumer G_i. Subnetwork search task Gr_i it is solved on the basis of the introduction of the reachability relation (→) vertices of the graph. For all nodes of the subnetwork, the reachability condition must be met, that is $\forall Gr_j \rightarrow G_i$. The search for subnetwork nodes is performed based on the transition to the reverse digraph $(G_j, G_i) \in Gr \Leftrightarrow (G_i, G_j) \in \overline{Gr}$. In the inverse graph, a set of vertices is defined for each consumer G^{*}, which are reachable from the vertice corresponding to the provider, that is $G^{*}: G_i \rightarrow G_j$. These are the vertices G^{*} represent the complete set of vertices of the subnet that provides the supplier's supply. Then all arcs whose beginning and end correspond to the vertices of the set are included in the subnetwork G^{*}, i.e. $e_{ij}: G_i \in G^{*} \wedge G_j \in G^{*}$. The calculation of this problem is performed on the basis of the Floyd-Warshell algorithm, which finds all the distances between the vertices of the inverse graph.

3. Results

We will assume that at each moment of time *t*, some flow diagram is implemented $F = (q_1, q_2, \dots, q_{|E|})$, which is consistent with the current value of the node cost vector $Q(t) = (Q_1(t), = (Q_1(t), \dots, = (Q_{|G|}(t))$. A necessary condition for the calculation F **of** the stationary mode is the first law of Kirchhoff $A * F = Q$, где $A = \|a_{ij}\|$ – the incidence matrix Gr dimensions $|G| * |E|$ and $a_{ij} = 1$, in case j-th the arc exits the node i, $a_{ij} = -1$, in case j-th the arch enters the i-th node and $a_{ij} = 0$ otherwise. It is known [6] that the first Kirchhoff law alone is not enough for an unambiguous choice of a flow diagram in order to ensure node costs. Additional conditions are required. As one of the models, the "*STANDARD_DU*" is used, in which the condition of the second Kirchhoff law for the potential difference is added.

The proposed method consists in the joint calculation of two stationary flow diagrams at once in order to minimize their mismatch in the selected metric:

$$W\left(F^{(1)}, F^{(2)}\right) \to min,$$
$$A * F^{(1)} = Q^{(1)}, \qquad A * F^{(2)} = Q^{(2)}, \tag{2}$$
$$F^{(1)} \leq P, F^{(2)} \leq P.$$

where $P = P(t)$ – the throughput matrix, which is calculated based on the state of the GTS model at time t using the matrix $M(t) = \|M_{ij}\|$.

For the Euclidean metric, the minimization criterion $W\left(q^{(1)}, q^{(2)}\right)$ determines as $W\left(F^{(1)}, F^{(2)}\right) = \left(F^{(1)} - F^{(2)}\right)^T * \left(F^{(1)} - F^{(2)}\right) W(\mathbf{P}^{(1)}, \mathbf{P}^{(2)})=(\mathbf{P}^{(1)}-\mathbf{P}^{(2)})^{T}(\mathbf{P}^{(1)}-\mathbf{P}^{(2)})$, and for a uniform metric as $W\left(F^{(1)}, F^{(2)}\right) = \sum_i \left|q_i^{(1)} - q_i^{(2)}\right|$.

Based on the concatenation of the original matrices

$$F^f = \left\|\begin{matrix} F^{(1)} \\ F^{(2)} \end{matrix}\right\|, A^f = \left\|\begin{matrix} A & 0 \\ 0 & A \end{matrix}\right\|, P^f = \left\|\begin{matrix} P \\ P \end{matrix}\right\|, Q^f = \left\|\begin{matrix} Q^{(1)} \\ Q^{(2)} \end{matrix}\right\| \tag{3}$$

problem (2) is reduced to a nonlinear programming problem with constraints in the form of equalities and inequalities:

$$W\left(F^f\right) \to min, A^f * F^f = Q^f, F^f \leq P^f, \tag{4}$$

and it is solved on the basis of the component model included in the modeling system.

The next problem to be solved is the problem of finding a single flow diagram F, but the closest to the given F^*. It is solved for the case when F^* is already used in the model at time t to provide node costs Q^* and at the next time $t+1$, a transition to a new flow diagram F is needed to provide node costs Q. After choosing the difference metric $W(F, F^*)$, the formal statement is reduced to the following form:

$$W(F, F^*) \to min, A * F = Q, F \leq F^*, \tag{5}$$

which is also solved based on the component model. In addition, transitions between flow diagrams with minimal mismatch (the minimum generalized distance $\sum_i \left|q_i^{(1)} - q_i^{(2)}\right|$on the graph of the flow diagram) will be accompanied by lower energy losses, which corresponds to combinations of energy criteria with criteria for the absence of a deficit.

Let, in general, during the control horizon, there is a change of three consumption modes $Q^{(1)}$, $Q^{(2)}$, $Q^{(3)}$ on the control horizon $[0, T] = [0, T_1] \cup [T_1, T_2] \cup [T_2, T_3]$. Let $Q^{(1)} = [1,6,5,2], Q^{(2)} = [1,7,5,1], Q^{(3)} = [2,4,7,1]$. Calculation of the joint combination of the first and second modes, then the first and third, and finally the second and third modes (table 1.) showed that, regardless of the combinations of consumption modes, the same flow diagrams were obtained. In addition, the Euclidean distances between the flow vectors are 1.55, 2.45 and 2.90, respectively, which corresponds to the ratio of consumption requests $Q^{(1)}$, $Q^{(2)}$, $Q^{(3)}$.

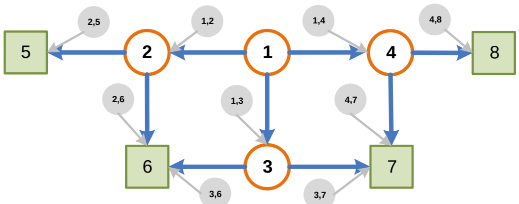
Table 1. Results of calculation of stationary flows

$\boldsymbol{Q^{(1)}, Q^{(2)}}$	**4.333**	**5.001**	**4.666**	**1.000**	**3.333**	**2.667**	**2.334**	**2.666**	**2.000**
$\boldsymbol{Q^{(1)}, Q^{(3)}}$	4,734	5.203	4.064	1.000	3.734	3.266	1.936	3.064	1.000
$\boldsymbol{Q^{(2)}, Q^{(3)}}$	4.330	5.003	4.667	2.000	2.330	1.670	3.333	3.667	1.000

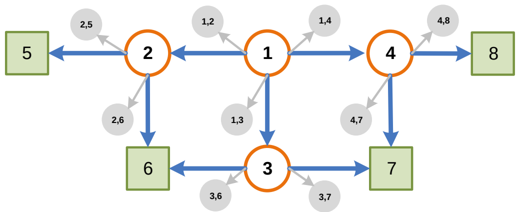
The calculation of the maximum planned deliveries to each consumer, that is, the search for real restrictions on requests by volume, is performed for each consumer G_i within the framework of its found supply subnetwork Gr_i based on linear programming methods using the corresponding software component included in the modeling system. Depending on the state of the entire network under conditions of non-stationary consumption, it is proposed to calculate stationary flow diagrams for each interval of constancy T_k=$[T_k^b, T_k^e]$ of node costs $Q(t)$ using formulas (1) or (3), and the sequence of transitions between calculated flow diagrams at specified time points sets the control procedure:

1. The intervals of constancy of node costs T_k=$[T_k^b, T_k^e]$, are formed, on which $\forall j$, $t_1 \in [T_k^b, T_k^e]$, $t_2 \in [T_k^b, T_k^e]$

2. The calculation of the first two flow diagrams is performed taking into account the given initial state of the system $M(0) = \|M_{ij}(0)\|$ and two vectors of node costs $Q^{(1)}$ and $Q^{(2)}$ based on (1). In other cases, for $k > 2$, the flow diagram $q^{(k)}$ is formed taking into account the current state of *M(t)* after the implementation of the previous scheme $q^{(k-1)}$ based on (3). The solution of these problems is performed for various graph structures, taking into account compliance or non-compliance with the balance: if the balance is met, then the calculation is performed according to the proposed scheme (5), if the balance is violated and consumption exceeds supplies, then the reserves are selected from all the PS. Formally, the flow diagram is calculated based on the inclusion of fictitious source vertices and arcs corresponding to the PS in the GTS digraph (figure 3). If the balance is broken in the other direction, that is, supplies exceed consumption, then all PS become additional drains. At the same time, a fictitious vertices of the drain and a corresponding arc are introduced for each PS (figure 3).



a) the scheme of sources



b) drainage scheme

Figure 3. Formation of schemes of fictitious sources and drains

3. Depending on the selected control criterion, the transition between flow schemes can occur due to a one-time change of all flows, or due to a smooth transition based on a weighted flow diagram for various stationary modes, which is defined as follows. Let F_1 and F_2 be two stationary flow diagrams, then the weighted flow diagram will be given based on the ratio $F(t) = \propto(t) * F_1 + (1 - \propto(t))F_2$ where $\propto(t)$ - is a monotonically decreasing function of time from 1 to 0.

In addition, for schemes with fictitious vertices, the maximum time for the implementation of the control action associated with a limited mass of gas in each UT is calculated. To increase this time, the criterion of the minimum mismatch is also added to the criterion of the minimum imbalance between the supply subnets of each consumer. The calculation of the time when implementing the scheme of fictitious drains is performed on the basis of the selected values of the maximum pressure in the gas pipeline, and the sources-on the basis of the minimum pressure.

4. Results discussion

The approach proposed in the paper for representing the GTS in the form of a digraph, with weighted vertices representing the vertices-drains of consumers, the vertices-sources of suppliers, transit vertices (compressor or gas distribution stations) and arcs indicating the main parameters that affect the throughput of the system as a whole, is used by most researchers [1,4,6,]. An original approach is to form a GTS subnetwork for a specific consumer and estimate the maximum flows for all consumers with pressure variations in all PS with a transition from the flow diagram under consideration to the closest one, which sets the procedure for controlling the GTS in a non-stationary consumption mode. A discrete-event analytical-simulation model has been developed, which, for a given GTS topology, the dynamics of supply volumes and consumption plans, allows to simulate the dynamics of supplies and implement a model time stretch with the formation of the state of the GTS in the form of a residual mass in all PS in accordance with the selected flow diagram. A system of criteria for optimizing the functioning of the GTS in a non-stationary mode has been formed, which allows forming various control algorithms for the simulation model due to the strategy of minimizing combinations of indicators of under deliveries and energy consumption, as well as maximizing the gas reserve in the pipes and the pressure balance in the entire studied GTS. As part of the formation of management strategies in the conditions of an imbalance of supply and consumption, schemes with fictitious sources and drains are proposed, procedures for switching to standard calculation schemes with the possibility of calculating the maximum times of its maintenance in the gas transportation APCS circuit are developed. A dynamic flow control procedure has been developed in the model of optimizing the management of non-stationary consumption modes, which is represented as a sequence of transitions between stationary flow diagrams based on minimizing their mismatch at neighboring time intervals corresponding to the intervals of constancy of consumption requests, which allows further reducing the energy costs of changing the flow diagram.

As a direction for the development of research in this direction, it is advisable to develop software and mathematical methods and means of interactive support for the activities of the manager in the decision-making process [17]. There are two main areas of such support:

- facilitating the interaction between data, data analysis and processing procedures and decision-making models, on the one hand, and the decision - maker, as a user of these systems – on the other;
- providing auxiliary information, especially for solving unstructured or poorly structured tasks for which it is difficult to determine the data and procedures for appropriate solutions in advance. That is, to create a decision support system that is open to the inclusion of new methods and models of the lower and upper levels, as well as optimization criteria (environment components).

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