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Multiple-criteria decision analysis for cross-country gas pipelines

Mikhail Sukharev [a 1], *Ruslan* Popov[a], and *Anton* Balchenko[a].

[a] *Gubkin Russian State University of Oil and Gas (National Research University), Moscow 119991, Russia*

Abstract. The paper considers the short- and medium-term planning problems of the regimes of multi-line technical gas pipeline corridors (MLGP) of Russian gas supply system. The fall in gas production due to the depletion of the gas fields leads to a decrease in the load of some operating MLGPs. At the same time, there is a redundancy of production capacities at compressor stations (CS). It becomes possible to use various technological schemes for incorporating CS with lines "pass by" in order to reduce the cost of gas pumping. The solution of the optimization task for the search for MLGP regimes in a one-criterion (minimum of the energy cost) formulation leads to frequent equipment switching. That is unacceptable. Therefore, it is advisable to proceed to multi-criteria statements, formalizing and introducing as criteria the requirements for the stability of technological schemes for switching on equipment, which are usually respected by the dispatch services. The purpose of this article is the development and testing of mathematical models and a computer program to support the adoption of dispatch solutions for managing modes of large MLGPs under conditions of incomplete loading. The solution method is demonstrated by the example of a three-line MLGP. The choice of optimal control is carried out using dynamic programming methods. In order to improve the quality of the choice of control actions, an algorithm is suggested that takes into account the stochastic nature of the loading of the MLGP.

1 Introduction

The multi-line technical corridors of the main gas pipelines (MLGPs) are the key trunks of the unified gas supply system of Russia. In some sections of MLGPs, 10 or more lines with a diameter of 1420 mm are laid parallel. Each compressor station of the corridor consists of several compressor shops (CSh). Loss of the gas pressure due to friction is replenished by gas compressor units (GCU).

2 The problem of multicriteriality in GTS control

[1] Corresponding author: mgsukharev@mai.ru

Technological aspects. The natural criterion for optimization in the control of gas transmission system (GTS) is the minimum of energy costs for pumping gas or a minimum of fuel gas costs. Small changes of multiline corridor capacity can be achieved by different variants for switching the gas compressor units on CSh's of the corridor. We call these variants technological schemes (TSs). Examples of TS for the fragment of the corridor are shown in fig. 2. With incomplete loading of the corridor, the differences by criterion on the minimum energy cost between the various TSs can be very small, and it is advisable to use different variants of the CSh switching off. When one CSh is disconnected, the corresponding line is "on the pass". Under conditions of incomplete loading, the strategy of short-term planning of regimes by one criterion will be erroneous. A single-criterion formulation of the optimization task will lead to a solution with frequent transitions from one version of the inclusion of equipment (TS) to another due to changes of flowrate. Such transitions, as a rule, are not justified from a technological point of view.
Experienced dispatchers tend to "jerk the regime" as rarely as possible. This allows to increase the reliability of gas supplies, increase longevity of GCU, facilitate dispatching control GTS. In the present paper, a variant of functioning is sought that provides a compromise of the requirements for minimizing energy costs and the desire for stability of the equipment regimes.

Brief review of the literature. The expediency of multi-criteria statements in the tasks of operational control and short-term planning of regimes of gas supply systems was noted more than once. In [3 – 6] is stated that although the formalized model provides a small saving of energy costs, but the significance of solutions increases, if one also takes into account the ecological effect: when fuel gas costs are minimized, emissions of greenhouse gases into the atmosphere decrease.

Actually, multi-criterial statements appear in [7 — 10]. Mantri & all [7] consider, as criteria, a linear combination of the total capacity of power equipment and the number of switching equipment at the CS, that is, the weighted sum of the cost and reliability criteria. Concrete numerical values of the weights are not given. Hawryluk & all [8] consider a one-criterion formulation (as a criterion, total costs for compression and cooling of gas are taken), and multi-criteria statements. Additional criteria are: maximum throughput, the amount of accumulated gas, gas temperature at the GTS outlet. The results presented in the article clearly show the possibilities of multi-criteria approaches.

In [10] the expert system is described, the requirements are put forward so that the fluctuations of the regime parameters are minimal, and the system control is as smooth as possible. The monograph [11] summarizes the experience gained in Russia in the creation and operation of automatic dispatch control systems. In particular, there is a list of criteria that are used in dispatching, moving from one to another if necessary, if the technological situation requires it.

A number of publications are devoted to models of hourly mode planning, in [12 — 14] computer information systems developed for this purpose are described. In [15] a two-criteria problem is considered: payments for environmental protection are added to the cost of gas for generating energy. It is recommended to find the optimal Pareto solutions and make the final choice using the "multi-evidence reasoning method".

3 Object of study, formalization

General information about the object. The kernel and technological goals of the proposed methodology are illustrated by a concrete example. A three-line MLGP (fig. 1) with a length of 900 km with 8 CSs is considered. The distance between adjacent CSs is 100 km. All pipelines have an outer diameter of 1420 mm and a wall thickness of 18.7 mm.

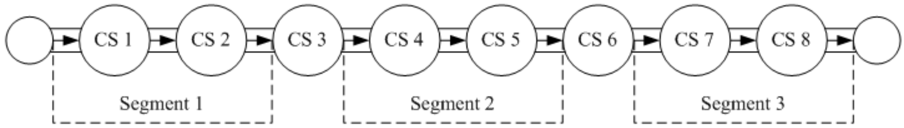

Fig. 1. Schematic diagram of MLGP

Single criteria problem. Most often as a criterion for optimizing the GTS modes, the minimum costs required for gas pumping are taken. For the case of MLGP (fig. 1), the formalization has the form of a mathematical programming problem.

$$Q_{fg}(q) = \sum_{i=1}^{M} Q_{fg,i}(q,\mathbf{z},\mathbf{u}) \to \min_{\mathbf{u}} \quad \textit{under condition } (\mathbf{z},\mathbf{u}) \in \Phi . \tag{1}$$

Here q – gas flow rate at the MLGP input, $Q_{fg,i}$ – costs of fuel gas at CS i, $\mathbf{u}$ – vector of control parameters, $\mathbf{z}$ – vector of mode parameters, Φ – acceptable region of the mode and control parameters, M – number of CSs.

Under actual control, the forecast of GTS modes for a certain period of time (day, week, month ...) is of the greatest interest. In this problem, it is necessary to take into account the unreliability of the forecast of the load. The results of the calculations presented below were obtained with the help of normative models of gas flow in pipes and GCUs applied in the Russian Federation [1, 2].

The problem is to find the control actions that ensure the minimum costs of fuel gas. We divide the components of the vector $\mathbf{u}$ into 3 groups $\mathbf{u} = \|u_1, \mathbf{u}_2, \mathbf{u}_3\|^T$: the first component $u_1 \in \{1,\ldots,N\}$ determines the technological scheme (TS) of the MLGP, that is, the option to turn off the CSh or, what is the same, the "on pass" lines, $\mathbf{u}_2$ – the number of GCUs operating in each CSh of the system, $\mathbf{u}_3$ – RPM rotation of GCU in each CSh of the system $\mathbf{u}_3 = \|\tilde{n}_1, \tilde{n}_2, \ldots, \tilde{n}_R\|^T$, R – the number of CShs. The scalar variable u_1 and the components of vector $\mathbf{u}_2$ are discrete, and the vector $\mathbf{u}_3$ components are continuous quantities. The search for optimal control $\mathbf{u}$ reduces to finding all components. The approach chosen by us is: when finding a variable u_1, an almost complete walk through variants is used, and by $\mathbf{u}_2$ and $\mathbf{u}_3$ an ordered search, dynamic programming, is used.

The system (fig. 1) is divided into 3 segments. Each segment contains three gas pipeline sections, and two CS between them. In fig. 2 presents 7 TS of segment (out of 20 possible) most frequently encountered in the optimal solutions. To select the optimal operating mode of the segment, the dynamic programming method [16] is used.

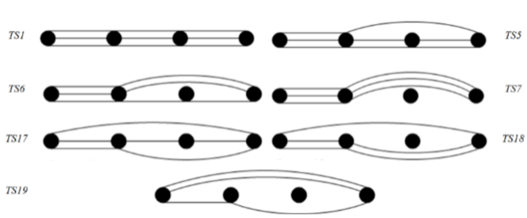

Fig. 2. Technological schemes of MLGP segment

For all 20 TSs optimal control settings $\mathbf{u}_2 = \mathbf{u}_2^*$, $\mathbf{u}_3 = \mathbf{u}_3^*$ and fuel gas costs Q_{fg}^* are calculated. Fig. 3 shows the dependence of the total fuel consumption on the volumes of transported gas in the optimal (under criterion (1)) variant. The graph is divided into fragments corresponding to different TSs (indicated in the fig. 3). It has gaps at the junction of two TSs, as well as within the same TS due to the change in the number of GSUs in the CSh. Fig. 4 shows ranges where each TS can be used without violating the technological constraints.

4 Results of calculations

Computational experiment. We now turn to the study of the modes of the corridor as a whole (Fig. 1). We carried out a computational experiment in which we calculated TCMG regimes under the following boundary conditions: the pressure at the inlet of the GTS is equal to p^{in} = 7.3 MPa, at the output – p^{out} = 5.2 MPa. In the experiment the criterial function $Q_{fg}^{TCPL}(q)$ – total fuel costs – was calculated.

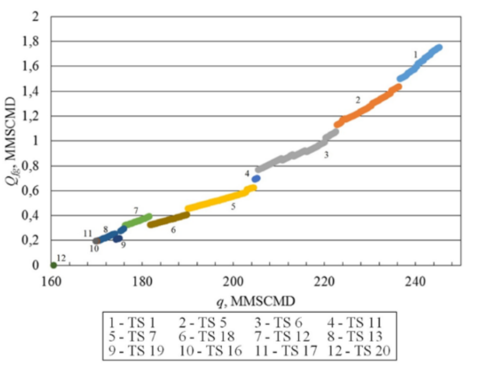

Fig. 3. Optimal solution for the segment: total fuel costs[1] Q_{fg}^{*} depending on the gas transported q

The function $Q_{fg}^{TCPL}(q)$ is represented by a convex down curve, which is well approximated by a square trinomial $Q_{fg}^{TCPL}(q) = 0.0003q^2 - 0.0651q + 3.6592$. In particular, this indicates that the unit costs for gas transportation increase significantly over the entire range of possible capacities. An optimization experiment was also conducted using not all possible TSs, but only the more rational ones depicted in fig. 2. The unit cost of transport increases, but this increase is very small. Note that the solution on a reduced set of TSs is more stable and besides requires 5 times less time for calculations.

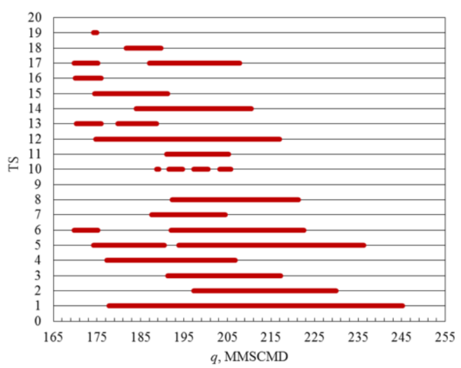

Fig. 4. Operation ranges of TSs – sets $\Omega_i,\ i = 1,\ldots,N$

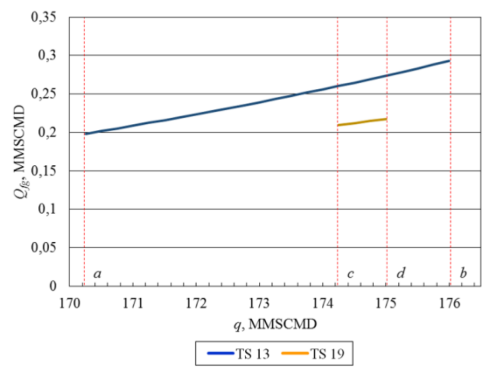

Fig. 5. Dependence of the total fuel gas $Q_{fg}^{TCPL}(q)$ on the flow rate q on the segment $[a;\ b] = [170.25;\ 176]$

Stability of control actions. To justify control strategies, to compare methods and algorithms designed to support operational decision-making, it is necessary to introduce an indicator or a system of indicators of stability. The purpose of the MLGP control is to find the best way to supply the consumers with the required quantities of gas $q_t,\ t \subseteq \Theta$. Here

Θ — the set of values of the time parameter, it can be discrete or continual. Let, for example, t be measured in days and consider the problem of forecasting the regimes for December. Then the discrete variant will be $\Theta = \{1,2,\ldots,31\}$, and continuous — the interval $0 \le \Theta \le 31$. Operating conditions include the structure of the system and technical characteristics of the power equipment, as well as the parameters of the regime at the beginning (pressure p^{in} and temperature T^{in}) and at the end (pressure p^{out}) of the TCMG.

In order to introduce the concept of stability of a TS, we define the sets Ω_i and Ω_i^*. They are calculated in the process of finding the optimal solution for each TS $i = 1,\ldots,N$. Set Ω_i is the totality of flowrates q permissible under TS i, and Ω_i^* is the totality of flowrates for which this TS is optimal. Sets Ω_i, Ω_i^* are the range of values of functions $\Omega_i = \Omega_i(\mathbf{u}_2, \mathbf{u}_3)$ and $\Omega_i^* = \Omega_i^*(\mathbf{u}_2, \mathbf{u}_3)$, respectively. The sets Ω_i, $i = 1,\ldots,N$ are shown in fig. 4 for all TS. In our example, all but one set Ω_i^* are segments. For TS 13 (2 lines pass by CS1 and CS2) the set Ω_{13}^* consists of 2 segments (fig. 5). The fig. 5 shows the graph of the function $Q_{fg}^{*TCPL}(q)$ on the interval Ω_i. TS 13 is valid throughout this interval, but on the subinterval $[c;d] = [174.25;\ 175]$ TS 19 is also permissible but leads to lower costs. The average cost of fuel gas in the interval $[a,b]$ under TS 13 is 0.243, and in the optimal variant, which provides switching from TS 13 to TS 19 and back — 0.233, that is 4% less.

It is naturally to consider the probability of an event $u_1 = i$ as a measure of the stability of a TS $u_1 = i$, consisting in the fact that this TS will not have to be changed during the operation of the MLGP. Consider the case when q is specified as a sequence of daily flowrates q_t, $t = 1,2,\ldots,T$ with a known probability distribution law. We introduce the following indicators:

$$p_i^* = P\left\{q_t \in \Omega_i^*,\ t = 1,\ldots,T\right\}. \tag{2}$$

$$p_i = p_i^* + P\{A_i / B_i\},\ \text{where } A_i = (\forall t,\ q_t \in \Omega_i),\ B_i = \left(\exists t,\ q_t \notin \Omega_i^*\right). \tag{3}$$

Here $P\{\bullet\}$ — the probability of an event $\{\bullet\}$, Ω_i / Ω_i^* — the difference of sets Ω_i and Ω_i^*, for example, $\Omega_{13} / \Omega_{13}^*$ is a segment $[c;\ d]$ (fig. 5). The value p_i^* is the probability that the TS $u_1 = i$, being optimal, will allow transportation of the required gas volumes without switching to another scheme. The value p_i is the probability that the TS i will allow transportation of the required gas volumes without switching to another TS, however, on the set Ω_i / Ω_i^* it will not be optimal.

The measure of the deviation of the solution: TS i is used on the whole set Ω_i — from the optimal solution is the value

$$\delta Q_{fg,i} = \sum_{t:q_t \in \Omega_i / \Omega_i^*} \left(Q_{i,t} - Q_t^*\right) \Big/ \sum_{t:q_t \in \Omega_i} Q_{i,t} = \sum_{t:q_t \in \Omega_i} \left(Q_{i,t} - Q_t^*\right) \Big/ \sum_{t:q_t \in \Omega_i} Q_{i,t}\ . \tag{4}$$

Changing the number of GCU for gas transportation personnel is easier than switching from one TS to another. However, the stability of the solution to the change in the vector $\mathbf{u}_2$ is characterized in the same way as the stability of control u_1 — the scheme of the CSh switching.

5 Optimization of control strategies

Model for presenting information about the forecast load. Let's discuss the problem of predictive mode planning. Let given a function $q = q(t)$ representing the gas consumption for the time interval until the end of the forecasting period. We will set the task of finding the best strategy for control the GTS for this interval. We need to discuss how to set the function $q(t)$. Demand for gas in the medium-term interval depends on many factors, most of which are random. The optimal is a compromise (in terms of complexity and adequacy) time series apparatus.
We tested the time series model

$$q_t = f(t) + X_t + \varepsilon_t,\ t = 1,\ldots,T\ , \tag{5}$$

where determinate function $f(t)$ describes trend, X_t – steady stochastic process, ε_t – discrete white noise. As X_t, the autoregression – moving average model [17] was used.

Optimization method. The control strategy should not be chosen a priori, but in accordance with the forecast consumption graph q_t. We used model (5), the advantage of which is the possibility of estimating its parameters by known methods. It is not possible to obtain analytical results in the problem of selecting optimal control strategies. An acceptable method here is statistical modeling — the Monte Carlo method.
In the process of modeling, sets Ω_i and Ω_i^* are formed by optimization calculations for each of the TSs considered (see Fig. 3, 4), and the parameters of the time series (5) are selected. A special algorithm has been developed for this. The algorithm allows to choose the best management strategy. Using the Monte Carlo method, estimates of the indicators (2 – 4) are calculated. TSs are ranked according this indicators. The value $p_i - p_i^*$ describes how much the stability of the TS will increase if it is used in situations where it is permissible, although not optimal. Indicator (4) describes what additional costs will be required when using a more sustainable TS instead of the optimal one. The choice of the optimal TS is made with the help of expert knowledge.

Conclusion

The aim of the paper is to develop a method of rational control and medium-term planning of large-scale GTSs regimes. The developed technique, along with the formal criterion of minimum energy costs for gas transportation, takes into account difficultly formalized factors of regime stability: the smallest possible number of switching on and off of compressor shops and GCUs. The stability of technological regimes helps to reduce equipment wear, increase its durability, and also entails other positive effects. Quantitative criteria have been introduced to characterize the stability of regimes.

The procedure is illustrated by an example of a 3-line MLGP with 8 intermediate CSs in conditions of incomplete loading. The technological modes of this object are investigated. An algorithm based on the ideas of dynamic programming has been developed for optimal control of the corridor according to the criterion of minimum gas transportation costs. The program that implements the algorithm is composed. As control actions on the operation modes of MLGP, the following are considered: switching-off and switching on of the CShs, switching-off and switching on of the GCUs, regulation of the number of revolutions of the centrifugal compressor of the GCUs.

The control actions of the highest level of the hierarchy have been studied in detail: the choice of the technological scheme, the various options for switching off/on the CShs. By the example of MLGP fragment by the method of computational experiment it is shown that out of 20 TSs it is enough to use 5 – 6 schemes for almost the entire range of possible flowrates. It is shown how the number of switchings affects the total costs of fuel gas.

The problem of forehand scheduling of modes for predictive loading is considered. Loading of the object for the period under consideration is given by a time series model including deterministic and stochastic components.

The algorithm based on the Monte Carlo method has been developed and is used to assess the stability indicators of TSs of MLGP. It is assumed that the final choice of the control strategy is made with the assistance of experts on the basis of a compromise between the total cost of fuel gas and the number of equipment switching. Indicators of stability modes, which are calculated using computer models are introduced.

The ideas demonstrated by the example of MLGP can be applied to gas transport systems of any structure.

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