Search of the most important combinations of gas industry objects from the positions of system operability

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Abstract. The article is devoted to the search and determination of the most important combinations of gas industry objects from the standpoint of system operability. The study was carried out on the example of the Unified Gas Supply System of Russia. The study is a development of the topic of the search and determination of critical objects of the system. Cases of simultaneous failure of two disconnected and independent from each other system objects are possible. The article presents a list of the most important combinations of gas industry objects that are not included in the list of critical objects, failure of which can lead to a significant gas shortage among consumers. Their significance and impact on the performance of the Russian gas industry are shown. Conclusions have been drawn on the feasibility of searching for such paired combinations of gas industry objects from the standpoint of system operability.

1 Introduction

The increase in the number of major accidents in energy systems in recent years has been due to the significant depreciation of fixed assets, and the lack of significant financial investments in their reconstruction. Large-scale accidents in energy systems resulting from the failure of the most important system objects entail significant, sometimes irreparable, damage to consumers in the form of large short deliveries of final types of energy.

In addition, geographically dispersed energy systems are becoming more intelligent and complex every year, more closely integrated with other infrastructure systems. Therefore, the failure of the most important system objects will have a negative impact on other interconnected infrastructure systems.

Thus, today it is relevant to identify the most important objects and their combinations in energy systems with the subsequent development of measures aimed at reducing the importance of such objects.

2 The current state of the investigated problem

In world practice, the study of the most important objects and their combinations in energy systems, the following points can be noted.

In [1, 2], the authors analyzed the gas transmission network to determine its most important components. The methodological approaches used are based on topological network analysis with an emphasis on the study of reliability and manageability. This analysis allows you to quantify the reliability of the gas transmission network and determine the role of each component of the network at various time intervals. As an example, the authors consider a real combined gas transportation network of several EU countries. The article presents the results of an analysis of such a critical infrastructure, and shows the need to take into account physical characteristics, such as restrictions on the throughput of gas pipelines. To assess the impact of negative external influences on the normal supply of gas to consumers, a special flow model was developed. Vulnerability analysis was carried out from three points of view: global vulnerability analysis, demand reliability analysis and critical analysis of gas pipelines. A global vulnerability analysis was conducted taking into account possible disruptions in the operation of gas sources and gas pipelines.

In [3], a method for detecting and ranking critical components and sets of components in technical infrastructures is presented. The criticality of a component or set of components is defined as the vulnerability of the system to failures when a particular component or set of such components fails. This issue also addresses the issue of multiple simultaneous failures with synergistic consequences that complicate the problem. The proposed method solves this problem. As a case study, a method for analyzing a gas distribution system in a Swedish municipality was presented.

In [4], the authors propose a comprehensive model for assessing the impact of the interdependence between electric and gas systems on the reliability of power supply to consumers. The mode of operation of the gas network was modeled using a number of restrictions. Restrictions on gas supplies may affect changes in the operating mode of the electric power industry. Case studies reviewed by the authors have proven this.

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In [5], an analysis of the possible effects in an integrated gas energy network is presented. Failures of the gas supply system, as has been shown, are considered more defining for an integrated energy supply system than failures in the energy supply subsystem itself. Accordingly, the authors drew attention to possible control actions aimed at minimizing the negative impact of failures in the gas supply system.

Studies [6, 7] are devoted to various issues of modeling energy systems as critical infrastructures. In [6], the authors propose an agent model of a typical regional power system, which includes the characteristics of specific types of plants and their cooling systems, which depend on adequate water supply at appropriate temperatures to support operation at full capacity. The study [7] presented a new approach to assessing the vulnerability of inter-city distribution gas pipeline networks caused by gas pipeline accidents. The effects of pipe-line failures are quantified based on the gas supply areas that they directly affect and the reduction in traffic efficiency caused by stops on the roads. This approach allows the identification of vulnerable links in a pipeline network that can not only have a significant impact on the pipeline network, but can also have a significant impact on the road network.

The study [8] examined and analyzed the problem of the vulnerability of critical energy infrastructures to terrorist acts on them. The study [9] offers a risk analysis methodology for systems of interdependent critical infrastructures in various extreme weather events.

The study [10] presents a probabilistic approach for identifying and ranking important components of the gas network in terms of supply security. The authors conduct a probabilistic risk analysis of the regional European gas transmission network for the selected attack scenarios. The results of 1 million Monte Carlo simulations in attack scenarios clearly indicate the various consequences for gas supply. Thus, the authors obtained a list of the most important infrastructure components.

In these articles, the authors come closest to determining the critical objects of the energy system, in this case the gas transmission network. At the same time, they assign different indexes to different objects of the system, which together determine the vulnerability of the system in case of disruption of this object.

A series of studies were conducted at ISEM SB RAS devoted to the identification of critical objects in the gas transmission network also were conducted studies focus on identifying critical facilities in the power industry [11, 12]. A list of crossings of main gas pipelines in the Unified Gas Supply System (UGSS) of Russia has been defined, the disruption of which will lead to a relative deficit of daily gas supplies through the system as a whole of 5% or more [13, 14]. Studies have been conducted to search for and determine combinations of individual sections of the main gas pipelines, the simultaneous disruption of which can lead to a significant shortage of daily gas supplies through the system (5% or more) [15, 16].

Studies have also been conducted that have identified critical combinations of gas industry facilities. Such objects were found, failure of which, coupled with one of the critical objects, will lead to a much greater gas shortage among consumers than if these objects fail separately [17]. After identifying possible critical combinations of objects in each case, the possibilities of bypassing bottlenecks by briefly increasing the throughput of individual sections of the main gas pipelines are analyzed. This technological measure was used to minimize gas shortages among consumers. As a result of such measures, the significance of a number of potential critical combinations of objects has been reduced. In this way, all possible critical combinations of gas industry objects are identified and their list is ranked by degree of importance.

At this stage of the research, it is proposed to find and analyze all the possible most important combinations of gas industry objects. The most important combination of objects in the framework of this study means a couple of unrelated, independent objects whose failure can lead to a significant gas shortage among consumers. Moreover, the objects under consideration should not be included in the list of critical objects, nor in the list of critical combinations of objects.

2 Definition of critical elements in energy systems

In this study, were used the flow model, which is the core of the "Russian Oil and Gas" software, to determine the critical objects itself and to search for critical combinations of objects [18, 19]. The use of this "Russian Oil and Gas" software allows user to determine the degree of satisfaction of gas needs within the country and ensure export supplies. In addition, the "Russian Oil and Gas" software allows user to identify bottlenecks — sections of network that in some cases limit the production capabilities of the system.

The flow distribution model in the Unified Gas Supply System of Russia in the "Russian Oil and Gas" software is designed to assess the production capabilities of the Unified Gas Supply System of Russia in conditions of various kinds of disturbances. The purpose of such studies is to minimize gas deficits at the consumption sites. The Unified Gas Supply System of Russia in the model is represented as a set of three subsystems: gas sources, main gas transport network and consumers.

When solving the problem of estimating the state of a system after a perturbation, the criterion of the optimality of the distribution of flows is the minimum gas deficit in the consumer with minimum costs for delivering gas to consumers. This problem can be solved by finding the maximum flow through the network, followed by minimizing the cost of gas delivery to consumers [20]. The mathematical formulation of this problem is described in [21].

In the flow distribution model in the Unified Gas Supply System of Russia, as already mentioned, the Basaker-Gowen algorithm is used to calculate the maximum flow of minimum cost, which as a result allows you to determine the possible level of gas consumer satisfaction. As a result of the implementation of various emergency situations, a gas shortage among consumers may occur due to a lack of flow capacity in certain sections of gas pipelines. Bypassing such narrow or limiting production possibilities of the system's places, in acceptable volumes, will allow reducing the gas shortage arising in the situation under consideration by consumers.

If there is a gas shortage among consumers caused by a lack of throughput capacities of the respective gas pipelines, other branches of the main gas pipelines not affected by the violation in question take on increased volumes of gas. In such a situation, the network congestion changes and a lack of throughput capacities in other sections of the main gas pipelines are possible.
The subsequent breakdown of bottlenecks in the gas transportation system will minimize gas shortages among consumers and will make the assessment and determination of possible critical combinations of gas industry objects as adequate as possible.

The "Russian Oil and Gas" software has graphical capabilities, which allows the researcher to identify many potential bottlenecks. These are objects that do not have a reserve of production capabilities, when analyzing the calculation results. Most often, such objects are either, or may become in the future, the reason for the shortage of the necessary amount of gas to consumers.

To solve the problem of circumventing the bottlenecks found, the flow distribution model included the possibility of incrementing the gas flow along edges within 10% of their capacity. Such a short-term increase in the throughput capacity of the main gas pipelines section is possible with an increase in the working capacity of compressors at large main compressor stations [22]. As a result of increasing the working pressure in the gas pipeline, an increase in the throughput capacity of the main gas pipeline section is achieved up to 10%. As a result (by using the technical capabilities of the gas transmission network), the problem of minimizing gas shortages among consumers is being solved.

3 Identification of the most important combinations of gas industry objects

The scheme of the Unified Gas Supply System of Russia used for the calculations in this paper on the flow model takes into account all the main features of the operation of the Unified Gas Supply System of Russia and contains:
- 382 nodes, including:
  - 28 gas sources;
  - 64 gas consumers (subjects of the Russian Federation);
  - 24 underground gas storage facilities;
  - 266 nodal compressor stations (CS);
- 486 edges representing main gas pipelines and outlets to distribution gas networks.

Initial data, such as daily consumption, extraction, export and import of gas, throughput capacity of existing gas pipelines are adopted in accordance with official statistics [23-25] for 2017. In a specially conducted study [26], an appropriate analysis was carried out, as a result of which 61 objects of the gas industry were assigned to critical gas industry objects. Among these objects there are 25 edges between the node compressor stations and 36 nodes, including 30 nodal compressor stations, 5 head compressor stations at the outlets from large gas fields and a compressor station on one underground gas storage.

Taking into account the previously obtained 61 critical objects and 630 pairs of critical combinations, calculations were carried out for pairwise shutdown of all other objects of the calculation scheme, followed by a "breakdown" of bottlenecks - measures aimed at minimizing the gas shortage among consumers. These calculations were carried out using the software package [27] detailing the functioning of the gas transmission network of Russia and allowing simulating various operating conditions of its facilities, including complete shutdown. The calculations were carried out using the parallel computing methodology at [28].

As a result, 2865 pairs of objects were selected from the 207690 pair combinations of objects, failure of which leads to a total gas deficit of 5% or more in the system. After solving the problem of bypassing bottlenecks, 2555 pairs of objects remained.

In the table 1 presents the results of determining the most important combinations of Unified Gas Supply System of Russia objects and the impact on them of the implementation of measures to circumvent bottlenecks, structured by their influence on the system.

Table 1. The results of determining the most important combinations of Unified Gas Supply System of Russia objects

Number of combinations		Gas shortage, %
Before bypassing bottlenecks	After bypassing bottlenecks	
4	0	15
10	6	11
18	14	10
51	39	9
101	54	8
243	167	7
1074	406	6
1364	1869	5

Table 1 clearly demonstrates that bypassing bottlenecks allows, in some cases, to significantly reduce the gas shortage among consumers. Table 2 presents 20 combinations of objects, failure of which can lead to a gas shortage in the system as a whole of 10% or more.

Table 2. Combinations of Unified Gas Supply System of Russia objects, failure of which will lead to a maximum gas shortage in the system as part of the study

№ of pair	Object type №1	Object type №2	Gas shortage, %
1	CS	CS*	11
2	CS*	CS	11
3	Edge	CS*	11
4	Edge	CS*	11
5	CS	CS	11
6	CS	CS*	11
7	CS	CS*	10
8	Edge	CS	10
9	Edge	Edge	10
10	Edge	CS	10
11	CS	CS	10
12	CS	CS	10
13	Edge	CS	10
14	Edge	CS	10
15	CS	CS*	10
16	CS	CS*	10
17	Edge	CS*	10
18	Edge	CS*	10
19	Edge	Edge	10
20	Edge	CS	10

When analyzing the table 2, it is necessary to highlight an object - one nodal compressor station (CS*), which is not included in the list of critical objects. CS* is present in 10 combinations from the table 2. In addition, this CS* is present in 25% of all combinations leading to a total gas deficit of the system as a whole of 5% or more.

In general, the following should be noted from the results of the study. Violation of the functioning of the most important combination of objects can lead to a significant gas shortage among consumers (5-15%).

In this situation, measures to bypass bottlenecks lead to a slight decrease in the gas deficit in the system as a whole (by an average of 2-3%). This fact confirms the high importance of the identified combinations. It is worth noting that in the framework of this study, as a result of bypassing bottlenecks, the number of possible most important combinations of objects was reduced by 10%.

4 Conclusion

This study examined the search for the most important combinations of gas industry objects. The definition of such combinations of gas industry objects, failure of which can lead to a gas deficit in the system as a whole, is comparable to the deficit arising from the failure of individual critical object. To search for the most important combinations of gas industry objects the "Russian Oil and Gas" software is used. This model is designed to assess the production capabilities of the Unified Gas Supply System of Russia under various disturbances. The main key combinations of gas industry objects received are analyzed in detail.

Studies have shown that in the modern configuration of the Unified Gas Supply System of Russia, there may be situations when, when a pair of network objects that are not critically important fails, the total gas shortage among consumers can reach up to 15% of the total gas demand. The definition and accounting of such combinations of objects is necessary to increase the reliability of the Unified Gas Supply System of Russia during its development and reconstruction work. The main efforts should be aimed at reducing the conditional significance of the identified specific critical combinations of objects for the health of the entire system.

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