Problems of searching for critically important combinations of gas industry objects from the position of ensuring energy security

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Abstract. The article is devoted to the problem of finding critical combinations of gas industry objects from the standpoint of ensuring energy security. A critically important object is the partial or complete failure of which can cause significant damage to the country from the fuel and energy complex as a whole or within a separate energy system. Gas transportation networks in Russia and Europe are very extensive, branched, and have many intersections and backup gas pipelines. Therefore, cases of simultaneous failure of several system objects are possible. The article presents the results of calculations in which the authors identify the most significant combinations of gas transportation network objects from the point of view of providing consumers with gas. The significance and influence of these combinations on the performance of the Russian gas industry is shown. Conclusions are drawn about the feasibility of searching for critical combinations of gas industry objects.

1 Introduction

Large, geographically distributed energy systems are exposed to a significant number of external threats. Among which the main ones can be identified are the aging and wear and tear of the linear part of fixed production assets, and the threat of deliberate impacts of various negative natures. Large-scale accidents in energy systems [1, 2], resulting from the failure of various critical objects of these systems, entail damage to consumers in the form of shortages of fuel and energy resources. Therefore, the search and determination of critical elements and their combinations in energy systems are important current problems.

2 Current state of the problem under study

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

In [3, 4], the authors analyzed the gas transportation network to determine its most important components. The methodological approaches used are based on topological network analysis with an emphasis on studying issues of reliability and controllability. This analysis allows us to quantify the reliability of the gas transmission network and determine the role of each network component at different time intervals. As an example, the authors consider a real integrated gas transmission network of several EU countries. The article presents the results of an analysis of such critical infrastructure, showing the need to take into account physical characteristics, such as gas pipeline capacity limitations. To assess the impact of negative external influences on the normal supply of gas to consumers, a special flow model was developed. The vulnerability analysis was carried out from three perspectives: global vulnerability analysis, demand security analysis and critical analysis of gas pipelines. A global vulnerability analysis was carried out, taking into account possible disruptions in the operation of gas sources and gas pipelines.

In [5] presents a method for discovering and ranking critical components and sets of components in technical infrastructures. The criticality of a component or set of components is defined as the vulnerability of a system to failure when a particular component or set of components fails. This problem also addresses the problem of multiple simultaneous failures with synergistic consequences that complicate the problem. The proposed method solves this problem. A method for analyzing a gas distribution system in a Swedish municipality was presented as a case study.

In [6], the authors propose a comprehensive model for assessing the impact of interdependence between electric and gas systems on the reliability of power supply to consumers. The operation of the gas network was modeled using a number of constraints. Restrictions on gas supplies may affect changes in the operating...
mode of the electric power industry. The case studies reviewed by the authors proved this.

An analysis of possible impacts in an integrated gas-energy network is presented in [7]. Failures of the gas supply system have been shown to be more critical to the integrated power supply system than failures in the power 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.

Research [8, 9] is devoted to various issues of modeling energy systems as critical infrastructures. In [6], the authors propose an agent-based model of a typical regional power system that includes the characteristics of specific plant types and their cooling systems, which depend on an adequate water supply at appropriate temperatures to maintain full power operation. The study [9] presents a new approach to assessing the vulnerability of intracity gas distribution and road networks caused by gas pipeline accidents. The impacts of pipeline failures are quantified based on the gas supply areas they directly impact and the loss of traffic efficiency caused by traffic disruptions. This approach allows the identification of vulnerable links in the pipeline network, which can not only have a significant impact on the pipeline network, but can also have a significant impact on the road network.

The study [10] examined and analyzed the problem of the vulnerability of critical energy infrastructures to terrorist attacks on them. The study [11] proposes a risk analysis methodology for systems of interdependent critical infrastructures under various extreme weather events.

Study [12] presents a probabilistic approach to identify and rank important gas network components from a security of supply perspective. The authors conduct a probabilistic risk analysis of the regional European gas transportation network under selected attack scenarios. Results from 1 million Monte Carlo simulations of attack scenarios clearly indicate different impacts on gas supply. Thus, the authors obtained a list of the most important infrastructure components.

In these articles, the authors come closest to identifying critical objects of the energy system, in this case the gas transportation network. At the same time, they assign different indices to different objects of the system, which collectively determine the vulnerability of the system if the operation of this object is disrupted.

A number of studies were carried out at the ISEM SB RAS to identify critically important objects in the gas transportation network. A list of intersections of main gas pipelines in the Unified Gas Supply System of Russia has been determined, the disruption of which will lead to a relative shortage of daily gas supplies throughout the system as a whole of 5% or more [13, 14]. Research has been carried out to search for and determine combinations of individual sections of main gas pipelines, the simultaneous disruption of the functioning of which can lead to a significant shortage of daily gas supplies through the system (5% or more) [15, 16]. Works [17 - 19] are devoted to the analysis of critical objects in electric power systems.

Research has also been carried out, as a result of which critical combinations of gas industry facilities have been identified. Facilities have been found, the failure of which in combination with one of the air purifiers will lead to a much greater gas shortage among consumers than if these objects fail separately [20]. After identifying possible critical combinations of objects in each specific case, the possibilities of bypassing bottlenecks by short-term increasing the throughput capacity of individual sections of main gas pipelines were analyzed. This technological measure was used to minimize gas shortages among consumers. As a result of these measures, the significance of a number of potential critical asset combinations has been reduced. In this way, all possible critically important combinations of gas industry facilities were identified and a list of them, ranked by degree of importance, was formed.

At this stage of research, it is proposed to find and analyze combinations of gas industry objects of three elements. That is, within the framework of this study, three unrelated, independent objects are considered, the failure of which can lead to a significant gas shortage among consumers.

### 3 Determination of critical elements in the gas industry

In the ongoing study, both to determine the critical important objects themselves and to search for critically important combinations of objects, a flow model was used, which is the core of the software-computing complex “Oil and Gas of Russia” [21, 22]. The use of this internal control system makes it possible to determine the degree to which gas needs are met within the country and export supplies are ensured. In addition, the software-computing complex “Oil and Gas of Russia” makes it possible to identify bottlenecks - sections of the gas transportation network that, in some cases, limit the production capabilities of the system.

The flow distribution model in the Unified Gas Supply System of Russia, laid down in the software-computing complex “Oil and Gas of Russia”, is intended to assess the production capabilities of the Unified Gas Supply System of Russia under conditions of various types of disturbances. The purpose of such studies is to minimize gas shortages at consumption points. The Unified Gas Supply System of Russia is presented in the model as a combination of three subsystems: gas sources, the main transport network and consumers.

When solving the problem of assessing the state of the system after a disturbance, the criterion for the optimal distribution of flows is the minimum gas deficit for the consumer at the minimum cost of delivering gas to consumers. This problem can be solved by finding the maximum flow through the network, followed by minimizing the cost of delivering gas to consumers [23]. The mathematical formulation of this problem is described in [24].

In the Unified Gas Supply System of Russia flow distribution model, as already mentioned, the Basaker-Gowen algorithm is used to calculate the maximum flow.
of minimum cost, which as a result allows us to determine the possible level of consumer satisfaction with gas. As a result of various emergency situations, gas shortages may occur among consumers, caused by a lack of throughput capacity of certain sections of gas pipelines. Bypassing such bottlenecks or areas of the system that limit production capabilities, in acceptable quantities, will reduce the gas shortage among consumers that arose in the situation under consideration.

If there is a gas shortage among consumers caused by a lack of capacity of the relevant 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 congestion of the network changes and a lack of capacity may appear in other sections of the main gas pipelines.

Subsequent debottlenecking in the gas transportation network will minimize gas shortages among consumers and makes the assessment and identification of possible critical combinations of gas industry facilities as adequate as possible.

To solve the problem of bypassing the identified bottlenecks, the flow distribution model included the possibility of increasing the gas flow through the arcs within 10% of their throughput. Such a short-term increase in the throughput of a section of the main gas pipeline is possible with an increase in the operating power of compressors at large main compressor stations [25]. As a result of increasing the operating pressure in the gas pipeline, an increase in the throughput of the main gas pipeline section by up to 10% is achieved. As a result (by using the technical capabilities of the gas transportation network), the problem of minimizing gas shortages among consumers is solved.

4 Calculation results

The Unified Gas Supply System of Russia calculation scheme used to model the operation of the Unified Gas Supply System of Russia in this work takes into account all the main features of the functioning of the Unified Gas Supply System of Russia and contains:

- 378 nodes, including: 28 gas sources; 64 gas consumers (subjects of the Russian Federation); 24 underground gas storage facilities; 266 hub compressor stations;
- 486 arcs representing main gas pipelines and branches to gas distribution networks.

Initial data, such as daily volumes of gas consumption, production, export and import, and the throughput capacities of existing gas pipelines are taken in accordance with official statistics [26-28] for 2019. In a specially conducted study [29], a corresponding analysis was carried out, as a result of which 61 gas industry objects were assigned to the Unified Gas Supply System of Russia critical important objects. Among these objects: 25 arcs between nodal compressor stations and 36 nodes, including 30 nodal compressor stations, 5 head compressor stations at the outlets of large gas fields and a compressor station at one underground gas storage facility.

A calculation was carried out for the simultaneous shutdown of three unrelated elements of the design circuit. These calculations were carried out using a software package [30] that reflects in detail the functioning of the Russian gas transportation network and allows simulating various operating conditions of its facilities, including complete shutdown. Calculations were carried out using parallel and distributed computing technologies [31].

As a result, 17,808,318 combinations of three elements were obtained, the failure of which could lead to a gas shortage of 5% or more in the system as a whole. As previously assumed [32], such a volume of output information is difficult to analyze further, so combinations of elements with a total deficit of 15% for the entire system as a whole were accepted for further consideration. There were 3,655,963 such combinations. The obtained quantitative calculation results are summarized in Table 1.

Table 1. Results of determining the most important combinations of UGSS objects

<table>
<thead>
<tr>
<th>Number of combinations</th>
<th>Gas deficit, %</th>
</tr>
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<tbody>
<tr>
<td>102</td>
<td>&gt; 50%</td>
</tr>
<tr>
<td>2421</td>
<td>40-50%</td>
</tr>
<tr>
<td>3655963</td>
<td>&gt; 15%</td>
</tr>
<tr>
<td>17808318</td>
<td>&gt; 5%</td>
</tr>
</tbody>
</table>

As shown in Table 1, in the current configuration of the Unified Gas Supply System of Russia there are 102 triplets of unrelated objects, the failure of which could lead to a gas shortage of more than 50% for the system as a whole. The most severe disruptions to gas supplies to consumers are 17 combinations, the failure of which could lead to a gas shortage of 52.8%. It should be noted that these combinations consist of the most significant critical facilities in the gas industry.

The calculation results show a synergistic effect from such disruptions in gas supplies to consumers. A detailed analysis of the combination leading to the occurrence of maximum gas deficiency showed the following. It consists of three critical facilities. Separately, the failure of these facilities using the same design scheme leads to the following gas shortages: 21.2%, 16% and 10%. These gas shortages add up to 47.2%, which is less than 52.8% if they fail together.

In general, from the results of the study it should be noted that disruption of the functioning of a combination of objects of three elements can lead to a significant gas shortage among consumers (> 50%).

4 Conclusion

This study examines the issues of searching for the most important combinations of gas industry facilities. The identification of such combinations of gas industry facilities was carried out, the failure of which could lead to a gas shortage in the system as a whole, comparable to the deficit that arose as a result of the failure of
individual water treatment plants. The obtained main most important combinations of gas industry objects are analyzed in detail.

The studies have shown that in the modern configuration of the Unified Gas Supply System of Russia, situations are possible when, if three network facilities fail, the total gas shortage among consumers may exceed 50% of the total gas demand. Determining and taking into account 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 performance of the entire system.

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