New Gas Pipelines as a Tool for Enhancing Reliability of Gas Supply to Consumers

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***Abstract*— This paper presents a set of tools for analysis of measures to compensate for compromised operation of critical facilities by identifying and creating new transmission routes beyond the arcs of the existing gas network graph. This study details and compares algorithms for network segmentation into basic polygons with isolated elements. Possible options are explored to minimize gas shortages during incidents at critical facilities, considering the integration of new arcs. This approach assumes that the unit cost of constructing new arcs is one to two orders of magnitude higher than that of existing mainline pipelines. The proposed toolkit is validated using a case study of Russia's Unified Gas Supply System, followed by an analysis of the findings.**

***Index Terms* — Reliability, extreme events, energy security, gas transmission system, large-scale pipeline transmission.**

I. Introduction

The current research agenda prioritizes identification of critical facilities (CF) of energy systems whose failure may cause mass disruptions in fuel and energy supply to consumers. Another topic of much debate is the search for measures to lessen the effect of such critical facilities on energy systems. Critical facilities in the gas industry are nodal compressor stations, crossings of mainline natural gas pipelines or individual sections of mainline natural gas pipelines that can severely limit gas supply in the event of their failure [1].

II. State-of-the-Art Review

The research on reliability of gas transmission under contingencies at gas industry facilities originates from critical infrastructure studies. The most seminal studies in this field include the following contributions.

Probabilistic methods of risk analysis are used for vulnerability assessment of infrastructural elements [2–4]. If historical data are available, statistical methods are used for analyzing and forecasting the effect of natural disasters on infrastructure performance [5]. Network approaches, such as the complex network theory, are used in vulnerability analysis of the infrastructural topology [6]. Recent years have seen a surge of interest in the research on interdependent infrastructures [7] and the effect of their interactions on overall vulnerability [8, 9]. The studies published, however, do not sufficiently address the development of measures to improve gas supply reliability in the event of the gas infrastructure failure.

The Melentiev ESI SB RAS conducts studies on the identification of critical facilities in the Unified Gas Supply System (UGSS) of Russia. These are the facilities whose failure may lead to daily shortages in gas deliveries of 5% or greater [10, 11]. The combinations of gas network facilities whose failure may lead to daily shortages in the entire system (5% or greater) are identified in [12, 13]. Their identification was followed by the investigation of each specific case for the possibility of bypassing "bottlenecks" by increasing throughput capacities of individual gas pipelines to reduce gas shortages for consumers.

The studies demonstrate that the existing structure of the gas transmission network in Russia has critical facilities whose failure cannot be compensated for by any of the

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considered measures, which necessitates new gas transmission capacity additions beyond the arcs of the existing equivalent network model. Study [14] focuses on network partitioning into simple polygons to create previously unconnected arcs. Additionally, a mathematical model for gas pipeline flow analysis was investigated considering the addition of new such arcs. However, manual identification of these arcs in large models proves unpractical. Therefore, we propose a set of dedicated tools to create new arcs.

III. A SET OF RESEARCH TOOLS FOR IDENTIFYING NEW ARCS

Key criteria guiding the search for reliability-enhancing new arcs are the completeness and size of a sample. If the sample is insufficiently exhaustive or does not include the new arcs that are important in terms of energy supply, the measures determined to lower the impacts of critical facilities on the energy system may fail to be effective and invariant with respect to the system. However, if the sample of new arcs is substantially larger than existing arcs in the model, the computational complexity involved in finding an optimal solution increases notably. Therefore, our design of the set of research tools prioritizes the methods that are capable of finding arcs inside subgraphs of a specified size.

There exist many methods for graph partitioning into subgraphs to simplify computation and analysis of this graph. Their choice depends on the nature of the problem. In our case, given that the graph is segmented in a pre-specified number of elements (starting from quadrilaterals), the main methods of analysis are the following:

1. Graph decomposition: hierarchical partitioning into subgraphs that relies on trees or other structures [15].

Graph decomposition assumes graph partitioning into overlapping sets of nodes arranged in a tree, which is most commonly achieved by:

- Treewidth decomposition (minimization of the tree width).
- Clique decomposition (graph decomposition into subgraphs).

The studies on clique decomposition were conducted in Melentiev ESI SB RAS [16] to identify critical facilities in the gas sector. Although the method performed well in identifying critical facilities, it failed to effectively find cliques of a specified size.

2. Grid embedding: graph representation as a grid preserving the original topology.

Grid embedding represents a graph as a rectangular grid where vertices correspond to corners of the rectangle, and edges correspond to its sides. The method can be used for graph partitioning into segments by combining geometric positioning with subsequent cluster analysis.

The method arranges graph nodes so that the adjacent nodes of the connected graph are close to each other and the arcs do not intersect, provided that the nodes are spaced uniformly [17].

However, given the complexity of gas transmission models and geospatial data processing, the solution resulting from graph embedding into a rectangular grid does not always capture realistically the state of the network due to frequent intersections of gas pipelines [18].

3. Cluster analysis with clusters of a specified size: clustering of nodes into connected subgraphs of a specified size.

The method divides the graph into clusters of a given size based on pre-specified features such as the degree of connectedness or geographical proximity.

Although the method succeeds in finding the closest non-overlapping polygons, given that facilities in Russia's gas transmission system can be located at a significant distance from each other, proper clustering is possible mostly for the European part of the country where the density of gas transmission facilities is higher.

4. Partitioning into *n*-cycles (C_4): decomposition of a graph into non-overlapping *n*-vertex cycles.

According to the graph theory, the cycle is a sequence of nodes that starts and ends at the same node. The division into n-cycles partitions the graph into non-overlapping subgraphs depending on the required number of elements in a cycle.

The method is effective in finding chordless cycles, i.e., the cycles where no two vertices are connected by an edge, except those that are already part of the cycle. The key advantage of this method is that it enables analysis of both high-density sections of the gas transmission network (e.g., in European Russia) and remote regions that have gas production capacities.

The n-cycle partitioning method was applied to design our research tools. Although the method is *NP*-hard in terms of finding all possible cycles in a graph [19], the time complexity of finding cycles with a given number of elements k is $O(2^k (V + E))$, where $O(V + E)$ is the time of running the depth-first search algorithm. Figure 1 shows an example run of the algorithm.

When using the tool, the user specifies information on the energy system as an oriented graph with the data on throughput capacity of arcs within the graph. The specified parameters also include constraints specific to the problem solved (constraints on the maximum length of the arc, constraints on the maximum cost of the arc construction) and the size of cycles that are to be found.

Gas pipeline flow distribution in the model meets the nodal gas balance conditions, adhering to Kirchhoff's first law. Nodal gas inflows are constrained by throughput capacities of arcs that depend on a number of parameters. These are the length, the diameter, the number of compressor stations, and the pressure in the pipeline modeled by an arc. The use of arcs with given throughput capacities enables the calculation of pressure drops along the pipeline length due to the local resistance and the gas consumed for process needs of the gas transmission network. This study assumes a 10% higher gas flow rate across the entire system to account for the above aspects of modeling. This value is based on multiple feasibility studies of the operation of the gas transmission system in Russia [20]. Therefore, Kirchhoff's second law is not required to calculate the gas flow rates and pressure drops along the gas pipeline length and at the local resistance sections.

The output produced by the tool is a map with the

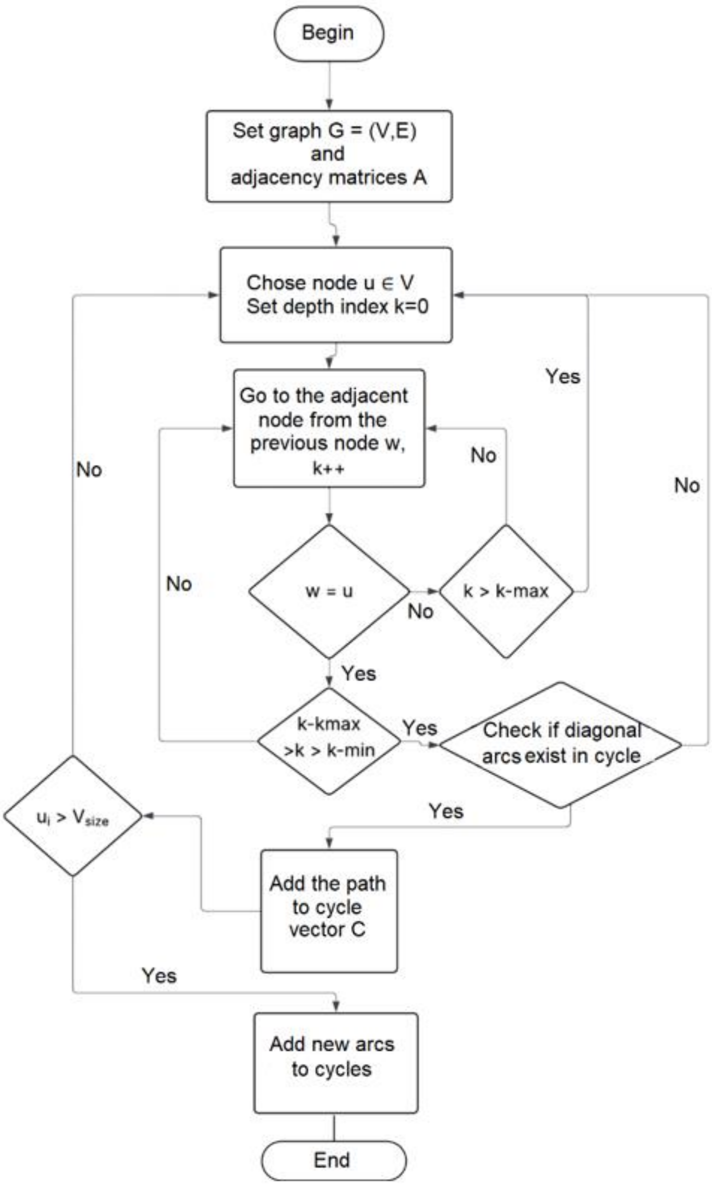

Fig. 1. The algorithm that uses polygons to identify new arcs.

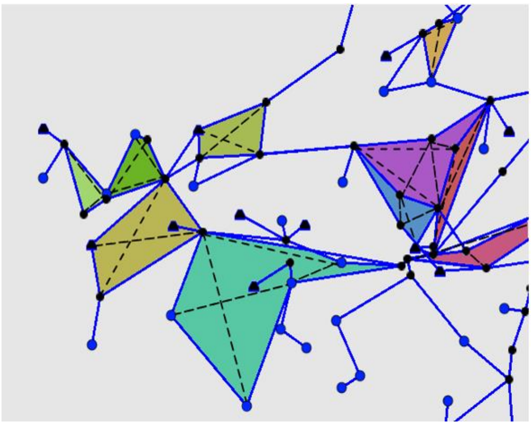

Fig. 2. Network segmentation and the search for new arcs aided by the proposed research tools.

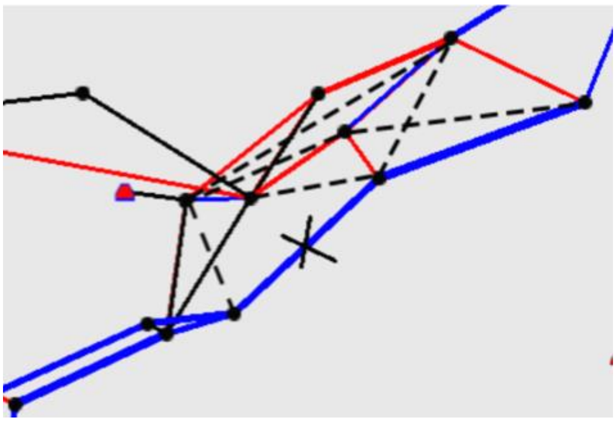

Fig. 3. A fragment of the USSG model with a disturbance and proposed new arcs (dashed).

network data including the found polygons and potential arcs (Fig. 2). The data on throughput capacity of new arcs is calculated based on the throughput capacity of the arcs within the cycle.

IV. Comparative Results

To test the above tools, we used an equivalent UGSS model with 645 arcs representing mainline natural gas pipelines and 383 nodes, including 28 natural gas sources, 64 consumers, 24 underground storage facilities, and 266 compressor stations.

The equivalent model was updated based on the data and reports published by Gazprom PJSC as the main operator of the Unified Gas Supply System [21]. Furthermore, to better align the equivalent model with the actual network, reports and research findings published by the European Network of Transmission System Operators for Gas (ENTSOG) were analyzed [22].

The input data such as daily gas consumption, production, exports, and imports, as well as throughput capacities of existing pipelines rely on the official statistical data for 2021 [23–25].

The designed research tool added 486 new arcs into the UGSS given the specified search size of all possible non-overlapping polygons $k = 6$. To find an effective set of new arcs, we modeled a disturbance that caused a gas shortage

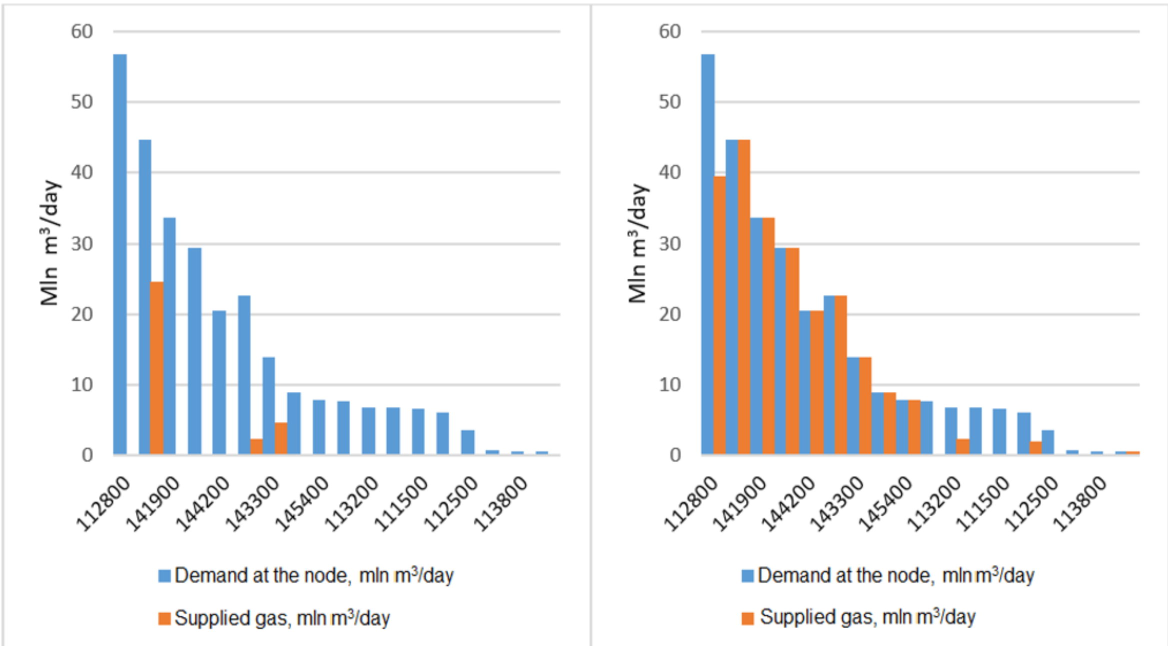

Fig. 4. The maximum gas shortage for consumers during the disturbance before and after the introduction of new arcs.

of 11.9% across the entire system. The calculations demonstrate that the introduction of 10 new arcs (Fig. 3) decreased the total shortage across the network from 11.9% to 2.9% (Fig. 4).

V. Conclusion

This paper proposes a set of research tools to identify additional gas transmission capacities beyond the arcs of the existing network graph. The tools partition the network into basic polygons by using cycles and then utilize the "Oil and Gas of Russia" software package to establish connections between previously unconnected nodes.

The method was validated on an equivalent network model of the UGSS. Further research will focus on the optimization of the polygon search algorithm to ensure its applicability to large-scale network configurations.

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