

The approach to determining vulnerable elements in critical energy infrastructures

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Abstract. The paper presents the main provisions of the methodology for identifying vulnerable elements in the fuel and energy complex, which is studied as a set of industry critical energy infrastructures. This methodology is based on the use of industry models system in the fuel and energy sector, on the analysis of the interconnected critical energy infrastructure's work in normal functioning and during emergency situations. The paper proposes a schematic diagram for the formation of vulnerable elements list for fuel and energy complex based on critical elements of industries. The scheme of work with a two-level system of models is given. The results of testing the methodology and developed models are presented (illustrative example).

1 Introduction^a

Critical infrastructures in accordance with the definitions [1, 2] with full confidence include industry energy systems and the fuel and energy complex (FEC), which is an interconnected infrastructure consisting of separate energy systems. This statement is confirmed by the importance of these infrastructures for the country's economy, supported by the need to ensure energy security, characterized as the state of protection of citizens, society, the state and the economy from threats of deficit in meeting their needs for energy resources of acceptable quality, from threats to disruption of uninterrupted energy supply. The main tasks to be solved in this case [3]:

- forecasting the conditions for the functioning and development of energy systems and the fuel and energy complex as a whole, taking into account possible critical and emergency situations;
- assessment of the condition under these conditions;
- identification of “bottlenecks” in the fuel and energy supply systems of consumers;
- the choice of alternatives, directions and specific measures to prevent emergency situations in systems or reduce their negative impact.

The consequences of the implementation of these emergency situations can lead to significant interruptions in reliable fuel and energy supply to consumers, and can cause a shortage of energy resources. This increases the relevance and need for models develop of critical energy infrastructures to

identify potential bottlenecks (vulnerable elements of critical infrastructures), assess their criticality for guaranteed and timely supply of energy needs. To conduct research with their help, a methodology for determining the critical (vulnerable) elements for the fuel and energy complex as a whole was developed and tested, presented below.

2. Methodology for determining critical elements

Studies to identify the most vulnerable elements (objects) of interconnected critical energy infrastructures (energy systems) are carried out on the basis of optimization of territorial-production models of functioning of the country's fuel and energy complex. In this case, the hypothetical calculated (non deficient or indignant) states of the fuel and energy complex are analyzed. Perturbed states are formed on the basis of single shutdowns of fuel and energy facilities, or for shutdowns of their groups. These disconnections at the model level are realized by a sharp decrease in the production capabilities of the objects, namely, the zeroing of the upper restrictions of the model variables corresponding to these objects. A comprehensive assessment of these conditions is carried out on the basis of their model indicators for various territories and for the analyzed critical infrastructures. For this, the criterion for the effectiveness of each infrastructure is used - relative energy shortages that are developing among consumers. Additionally, it is possible to consider the using of the industries reserve capabilities - fuel reserves, reserves of generating capacities in electric and heat power engineering, and the possibility of diversifying fuel at double fuel supply facilities.

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To assess the criticality of the fuel and energy complex object in the framework of optimization calculations, the element significance criterion is used, which characterizes the relative changes in the analyzed model parameters when the functioning mode of this object changes over the entire set of states. Formally, this indicator is given by formulas (1):

$$ZO_i = \sum_{j=1}^J ZO_i^j * ZC^j \quad (1)$$

ZO_i – significance of the i -th the fuel and energy complex object ;

ZO_i^j – assessment of states according to the j -th model indicator (relative energy shortage) when the i -th element is turned off ;

ZC^j – priority of the j -th indicator ;
 J – number of analyzed indicators (energy shortage, depletion of reserves, capacity reserves, etc.) ;
 I – plenty disconnected critical elements of the fuel and energy complex.

The research scheme (Fig. 1) is formally represented by three stages:

– the stage for the formation of the strategy for selecting critical objects;

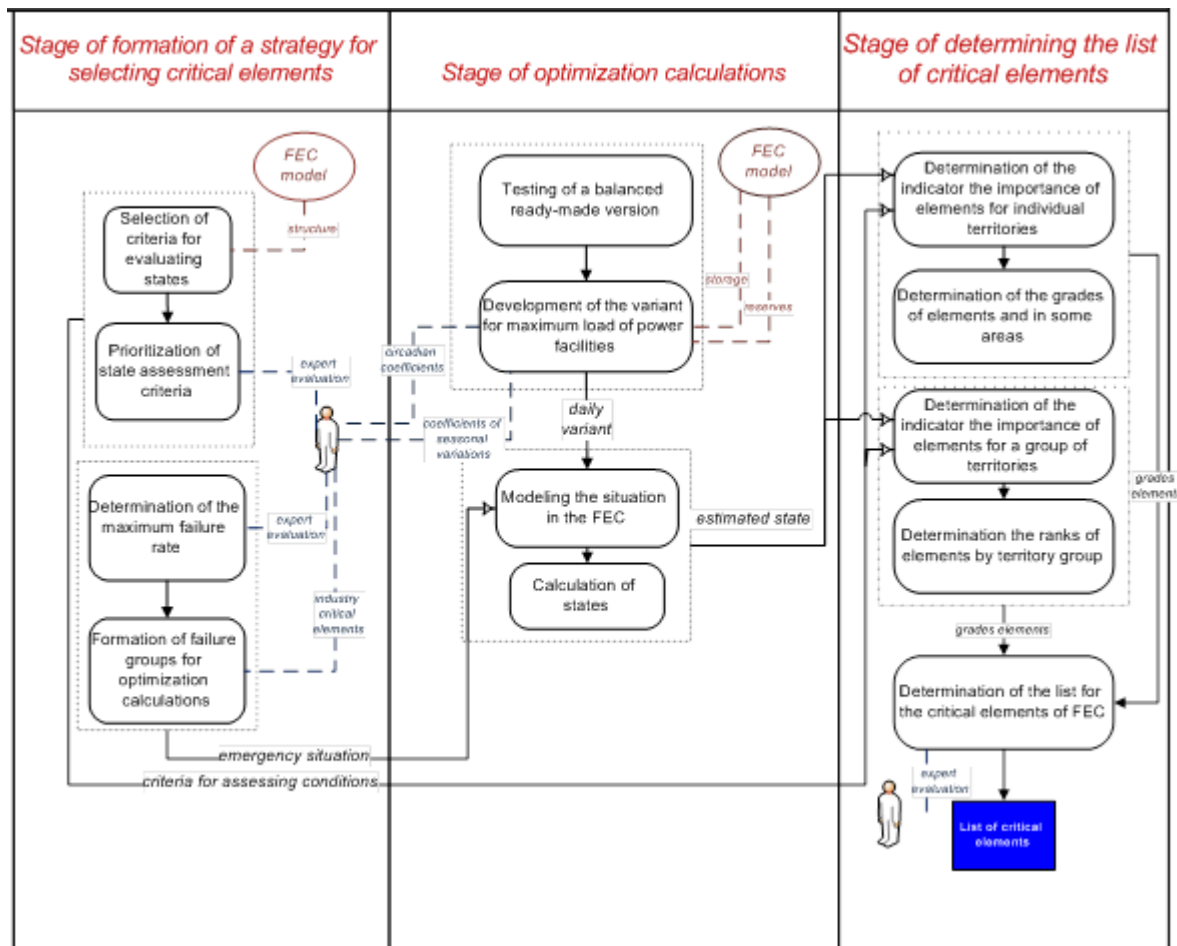


Fig. 1 A generalized search scheme for critical elements in the framework of model calculations

– the stage of carrying out optimization calculations;
 – the stage of forming a list of critical objects based on their calculated significance indicators.

At the first stage

- objects of the simulated FEC territorial-production structure are determined;
- groups of disconnected elements are formed for their subsequent inclusion in simulated situations;
- a set of criteria for assessing states (relative model indicators) is formed, the significance of these criteria is determined

- categories of elements criticality and their threshold values are determined;
 - emergency situations scenarios are being formed.

At the second stage, optimization calculations of the fuel and energy complex model are carried out, in the framework of which:

- balanced annual version of the statistical information is being debugged;
- the variant for the daily maximum load in energy systems is being debugged;

- abnormal situations are calculated with various options for disconnecting potential vulnerable elements.

At the third stage, the results of assessing the state of critical infrastructures when disconnecting the specified elements are formed:

- the composition of the analyzed calculated states is corrected by excluding the states with a relative deficit acceptable for the country as a whole for at least one resource;

- criteria for the significance of elements for the territories or their groups are determined;

- the ranks and categories of criticality for the analyzed elements are determined;

- a list of critical elements for the fuel and energy complex is formed.

3. An illustrative example of testing the methodology

The methodology was tested on the basis of daily model for the functioning of the fuel and energy complex. Therefore, when choosing critical elements of the fuel and energy complex, three types of daily variants for the model are formed: the average daily balanced option, the

maximum load variant for energy facilities, and variant for disconnecting industry-specific critical elements with a maximum workload of facilities. In the last two cases, when deficits arose, model mechanisms of structural redundancy of systems in the form of reservation and diversification of energy resources became active.

This model represents the territory of the country by 79 subjects of the federation. Technologically, model consists of industry subsystems of the energy complex (gas, coal, oil refining (in terms of fuel oil supply), and electricity and heat industries) [4].

A number of experimental calculations were carried out in which, as design conditions, the influence of the disconnection of critical elements of the gas industry [5] on the functioning of the fuel and energy complex as a whole was analyzed. The result of a turn-off of selected gas industry facilities was the under-production of the energy resources considered in the model and, accordingly, their shortage among consumers.

In the whole country, for each switch-off facility in the gas industry, the following situation has developed, Fig. 2.

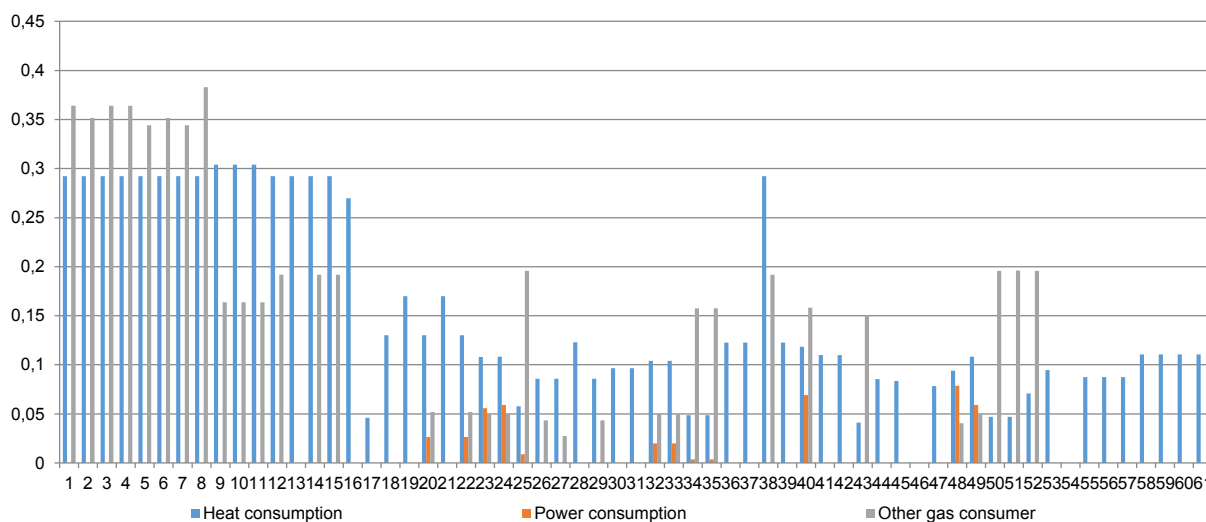


Fig. 2. The relative shortage of energy resources when turning off critical elements of the gas system, the share of units

When determining the coefficients of significance, potential critical elements were discarded, when energy shortages amounted to less than 5% of the needs. As a result, from the initial list of 61 critical elements in the gas industry, 52 elements remained, the disconnection of which led to more significant shortages (Fig. 3).

The analysis of the obtained graphs showed that the ranked list of critical elements of the gas industry almost corresponds to disconnections of these elements during the mutually agreed operation of all energy systems in a single complex (fuel and energy complex) with rare exceptions.

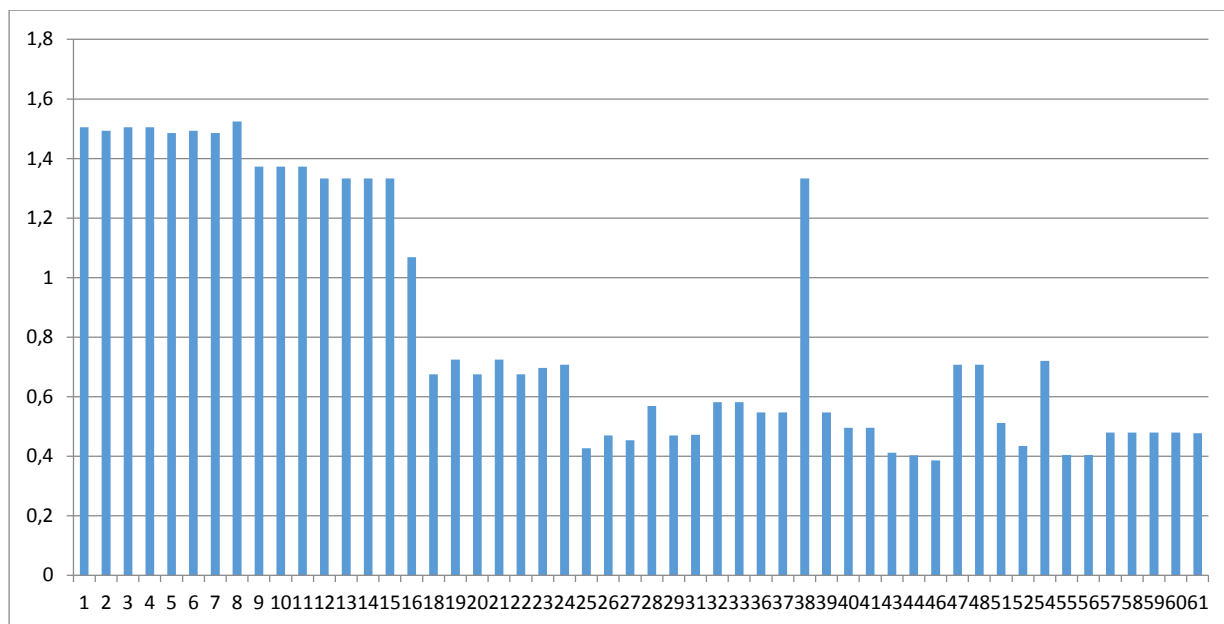


Fig. 3. The coefficients of significance of the critical elements of the gas system

According to the obtained coefficients of significance, three categories of critical elements were identified by their impact on energy supply (by the magnitude of the deficit from their shutdown): 1 category, in which elements causing a total relative deficit of more than 70%, 2 category from 30 to 70%, 3 category - below 30%. The number of critical elements for these groups throughout the country (in federal

districts) was distributed as follows (Table 1). A significant deficit was obtained in territories whose fuel and energy balance is focused on the use of natural gas. This is the North Caucasian, Southern and Volga regions, where the number of critical elements of the first category ranged from 17 to 25.

Table 1. Classification of critical elements of the gas industry by the impact on energy supply to consumers

Federal District	1 category (70-100%)	2 category (30-70%)	3 category (0-30%)
Central	15	3	34
Northwestern	14	27	11
South	17	20	15
North Caucasian	25	17	10
Volga	17	15	20
Ural	6	7	39
Siberian	5	3	44
Far Eastern	3	49	-

Further, critical elements were considered according to the technological criterion: sources (gas production enterprises) (Fig. 4), compressor stations (Fig. 5), sections of main gas pipelines (Fig. 6). The coefficients of significance of these elements differ in the depth of

the deficit caused by them in the territories under consideration. A significant deficit causes shutdowns of the compressor stations and individual sections of gas pipelines.

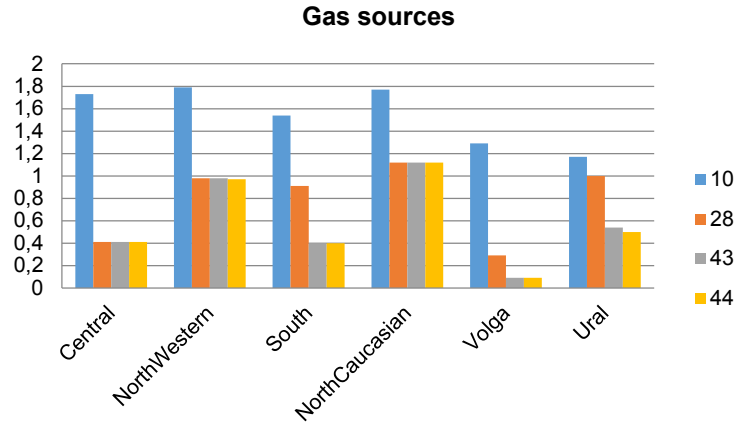


Fig. 4. The coefficients of significance of critical elements of the gas system by district

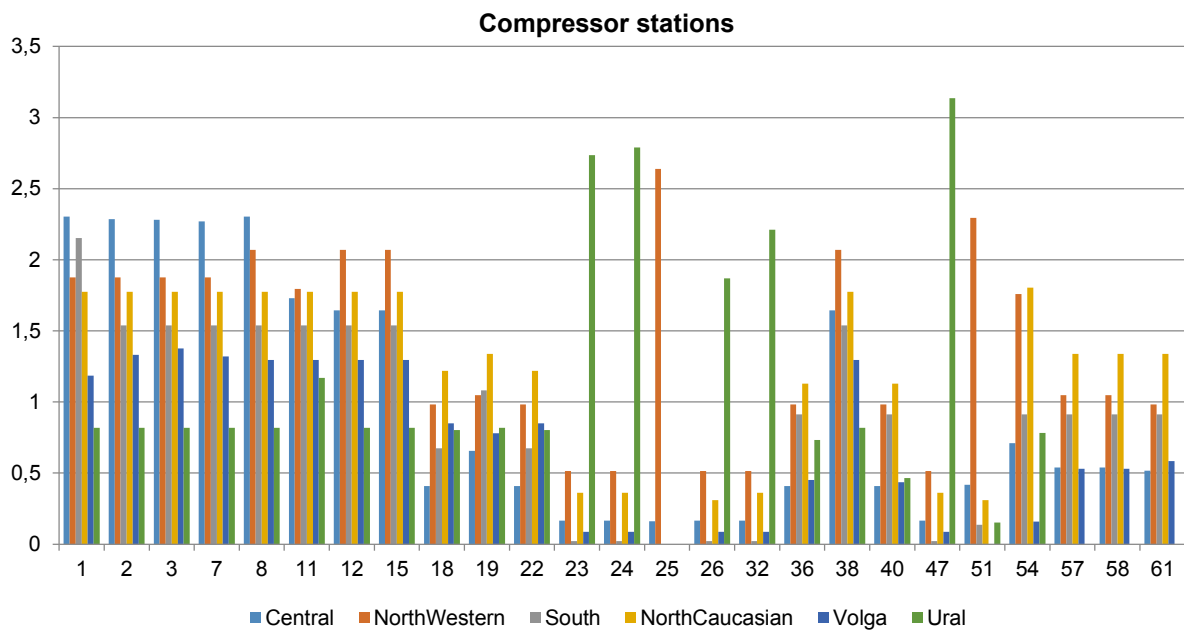


Fig. 5. The coefficients of significance of critical elements of the gas system by district

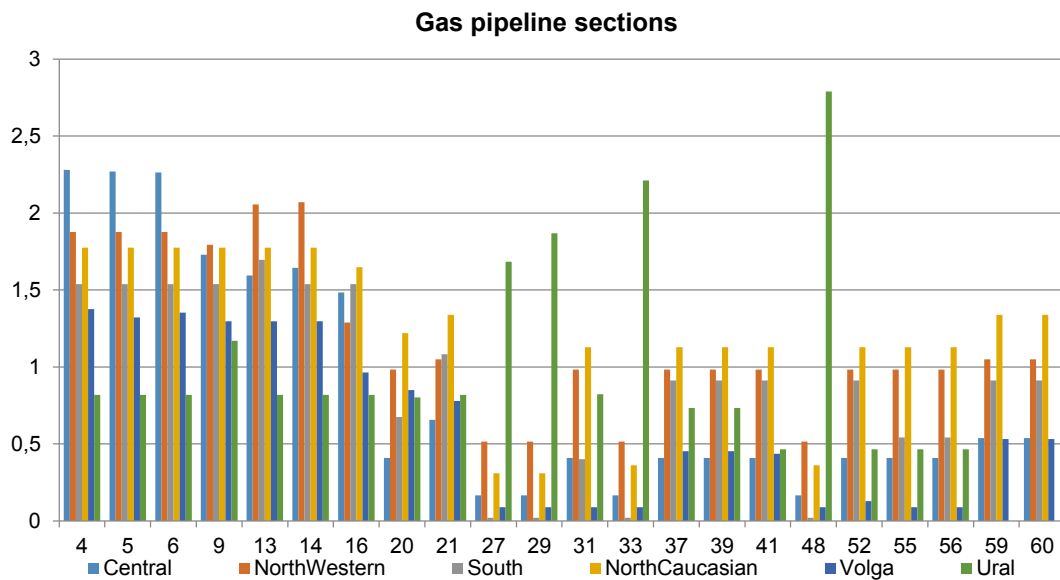


Fig. 6. The coefficients of significance of the critical elements of the gas system by district

An analysis was made of the frequency (repeatability) of the entry of vulnerable elements into the most critical first category in all federal districts. It turned out that these are mainly compressor stations and sections of gas pipelines, the frequency of which is 5 and 6, from the sources - one element, the frequency of which in terms of repeatability across the territory was 4.

This example illustrates the results of experimental studies evaluating the significance of elements of the gas industry for reliable energy supply to consumers in a single complex. Similar studies to identify critical elements and reliable energy supply are carried out in the electricity industry [6, 7]. In the future, it is planned to carry out experimental studies to assess the importance of critical elements of the electric power industry for the operation of the entire fuel and energy complex, as well as combinations of elements of the gas and electric power industries in analyzing the reliability of energy supply to consumers.

4. Conclusion

The paper presents the main provisions of the methodology for determining critical (vulnerable elements) in the fuel and energy complex. This methodology is based on the use of a hierarchical system of models of industries in the fuel and energy sector, on the analysis of the interconnected work of industry critical energy infrastructures in normal functioning and during emergency situations. The results of testing the methodology and developed models for studying the influence of critical elements of the gas industry on the mutually agreed work of the energy industries in a single complex are also presented. The coefficients of significance of the elements under consideration, taking into account the systemic effect, are obtained.

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