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# Comprehensive analysis of multi-energy system vulnerability

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This article proposes a framework for comprehensive vulnerability analysis of a multi-energy system (energy infrastructure), consisting of several stages. The framework uses previously implemented algorithms of discrete multi-criteria selection to find optimal options for the functioning of the energy infrastructure. Also, it performs processing, storage and analysis of natural-climatic and socio-economic data for monitoring the processes of functioning of energy infrastructure facilities.

*Keywords:* multi-energy system, resilience, vulnerability analysis, multi-criteria choice.

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## Introduction

Resilience is the ability of a multi-energy system (energy infrastructure) to adapt to various major disturbances and recover to the state in which it was before their impact. The purpose of the study of survivability is to develop strategies to increase it, the purpose of which is to improve the system's response in response to the effects of the considered large disturbances [1].

Vulnerability and risk analysis is the basis for the study of the survivability of energy infrastructure, as it plays a central role in supporting decision-making to improve survivability [2].

The concept of vulnerability in the literature has two closely related interpretations [3]. In the first case, vulnerability is considered as a global system property that expresses the size and scale of negative consequences as a result of the impact of a particular disturbance. In the second case, the vulnerability has a local meaning and represents an element of the system, the failure of which has large-scale negative consequences for the system.

The vulnerability analysis of the energy infrastructure should solve the following methodological problems:

- quantification of vulnerability;
- comparison of different system configurations by vulnerability.

In this article, the values of quantitative vulnerability indicators are determined as a result of processing, storing and analyzing information related to the functioning of the energy infrastructure. Part of the information, such as natural-climatic and socio-economic data, is obtained by monitoring the processes occurring at energy facilities. The indicators act as criteria for discrete multi-criteria selection algorithms, which are used to select the most severe perturbation scenarios in terms of consequences. Further, according to the graphs of the decline in the performance of the energy infrastructure built on the basis of selected disturbance scenarios, various configurations are compared by vulnerability. The same indicators and algorithms are used to search for elements of energy infrastructure, the failure of which poses the highest risk of under-supply of certain types of energy resources for various categories of consumers.

## 1. Related Work

Considering the structural and dynamic complexity of modern critical infrastructures (CIs), the need to take into account the relationships between them and uncertainties of various kinds, emphasizes [2] that the assessment of the vulnerability of CI must be carried out from different perspectives, for example, from the point of view of economics [4] or management theory [5, 6]. Each perspective can rely on its own method of modelling CIs.

The CI modelling method defines the basis for the study of its vulnerability in the local and global sense. On the one hand, the choice of indicators of the criticality of CI elements depends on the modelling method. On the other hand, it outlines possible ways to measure system performance, the decline of which is due to the impact of a large disturbance and characterizes the vulnerability of the CI in relation to this disturbance. Thus, for a comprehensive vulnerability analysis, integration of various approaches to CI modelling is required [2].

The idea of integrating various CI modelling methods for a comprehensive vulnerability analysis can be traced, for example, in [7], where the electricity transmission network is analyzed from four different points of view in order to identify the most important elements. In [8], the authors, comparing reliability and vulnerability analysis on the example of electric power systems, conclude that vulnerability analysis should serve as an addition to various types of probabilistic risk analysis. In [1, 9], the gas transmission network is considered from several aspects: reliable fuel supply to consumers, topology and controllability. A general approach for analyzing the vulnerability of critical infrastructures from these points of view is already proposed in [11]. The work [1] combines a multi-product flow problem and a model for studying the economic relationships of various industries to quantify the effects of disturbances in the transport network on industries and assess the importance of network elements.

## 2. Comprehensive vulnerability analysis of an energy infrastructure

Considering the above, in [13] the authors proposed a new approach to the complex analysis of the vulnerability of energy infrastructure, based on the idea of integrating various approaches to modelling CI [14].

A comprehensive analysis of the vulnerability of energy infrastructure provides:

- consideration of relationships of different types [2];

- quantitative assessment of vulnerability from a topological and functional perspective [11];
- universality in relation to different classes of disturbances and different levels of territorial and technological hierarchy [1];
- effective use of high-performance computing to accelerate calculations and analyze their results.

The input information for vulnerability analysis are classes of disturbances and measures to improve survivability, a list of vulnerability indicators, and the configuration of energy infrastructure.

Perturbations are divided into the following classes:

- natural disasters such as floods, earthquakes, hurricanes, etc.;
- man-made disasters caused by failure of components or subsystems;
- deliberate (intentional) violations, such as terrorist acts, cyber-attacks, etc.

Measures to increase survivability include actions to improve the security of energy infrastructure facilities before a major disturbance, as well as steps aimed at countering and absorbing the disturbance after its occurrence.

As part of a comprehensive vulnerability analysis, the energy infrastructure is considered as a meta-system consisting of several interconnected energy systems. The configuration of the energy infrastructure is understood as a description of the territorial and production structure of individual energy systems and the connections between them, natural and climatic factors and socio-economic conditions of their functioning. The method of forming a series of natural and climatic data is described in [15]. Monitoring of technological and socio-economic parameters of the functioning of energy infrastructure facilities is presented in [16].

Vulnerability indicators, as mentioned above, are closely related to the method of modelling energy infrastructure.

## 2.1. Modelling a disturbance

The scenario of a major disturbance consists of several time periods $T$. If $v_t$ is denoted the impact of the disturbance over a period of time $t = 1, \dots, T$, the model of functioning of the energy infrastructure as a meta-system in a period of time $t$ can be represented as the following optimization problem:

$$(\mathbf{cx}_t + \mathbf{bs}_t) + \mathbf{pz}_t + \mathbf{hu}_t \to \min, \tag{1}$$

$$\mathbf{s}_{t-1} + A_t(v_t)\mathbf{x}_t + Q_t\mathbf{u}_t - \mathbf{y}_t - \mathbf{s}_t \geq 0, \tag{2}$$

$$\mathbf{y}_t + \mathbf{z}_t = \mathbf{R}_t, \tag{3}$$

$$\mathbf{x}_t \leq \mathbf{D}_t(v_t), \tag{4}$$

$$\mathbf{y}_t \leq \mathbf{R}_t, \tag{5}$$

$$\mathbf{z}_t \leq \mathbf{R}_t, \tag{6}$$

$$\mathbf{u}_t \leq \mathbf{U}_t, \tag{7}$$

$$\mathbf{s}_t \leq \mathbf{S}_t(v_t), \tag{8}$$

$$\mathbf{s}_0 = \mathbf{S}_0, \tag{9}$$

where $\mathbf{x}_t$ — the vector, the elements of which characterize the intensity of the application of technological methods of functioning of energy facilities (extraction, processing, transformation and transport of energy resources); $\mathbf{y}_t$ — the vector, the elements of which characterize the volume of consumption of certain types of energy resources by different categories of consumers; $\mathbf{z}_t$ — the vector, the elements of which are equal to the under-supply of certain types of energy resources to various categories of consumers; $\mathbf{u}_t$ — the vector describing the intensity of measures to increase the survivability; $\mathbf{s}_t$ — the vector, the components of which characterize the volume of fuel reserves; $A_t$ — the matrix describing the technologies of production and transmission of energy resources, the values of the elements of which depend on the impact of the disturbance $v_t$; $\mathbf{D}_t$ — the vector that determines the technically possible intensities of application of individual technological and production methods, the values of the elements of which depend on the impact of the disturbance $v_t$; $\mathbf{R}_t$ — the vector whose elements demonstrate the needs for certain types of energy resources for various categories of consumers; $Q_t$ — the matrix reflecting the localization of measures to improve survivability; $\mathbf{U}_t$ — the vector that sets the limits of the intensity of measures to increase survivability; $\mathbf{S}_t$ — the vector defining the storage capacity, the values of the elements of which depend on the impact of the disturbance $v_t$; $\mathbf{c}$ — the vector, the elements of which determine the unit costs for each technological method of functioning of the elements of the energy infrastructure; $\mathbf{b}$ — the vector of unit costs for storage operation; $\mathbf{p}$ — the vector of specific damages resulting from the under-supply of certain types of energy resources to consumers; $\mathbf{h}$ — the vector that sets the unit costs for the preparation and implementation of measures to improve survivability.

The objective function (1) is a convolution of three criteria. The first criterion reflects the costs associated with the functioning of the metasystem. The second criterion evaluates the damage caused by the shortage of energy resources due to the impact of the $v_t$ disturbance. The costs of preparing and carrying out measures to improve survivability are characterized by the third criterion.

The impact of the $v_t$ disturbance is realized by changing the values of the matrix components $A_t$ and the vectors $\mathbf{D}_t$, $\mathbf{S}_t$ in the equations (2), (4) and (8), respectively. Their elements characterize the degree of deformation of various components due to the effects of perturbation over a period of time $t$. The consequences $\mathbf{z}_t$ from the impact of the perturbation $v_t$ are determined by equation (3).

The level of necessary supply of consumers with certain types of energy resources is given by equation (4). Technical restrictions on carrying out measures to increase survivability are defined in (7).

The volume of fuel reserves in storage facilities in the time period $t$ is limited by their available capacity according to inequality (8). Equation (9) assumes that at the beginning of the disturbance (in the time period $t = 0$) all storage facilities have some initial reserve of energy resources described by the vector $\mathbf{S}_0$.

The territorial and production structure of individual energy systems and the connections between them is fully represented in the matrix $A_t$. Natural and climatic factors and socio-economic conditions of the functioning of the energy infrastructure form separate components of the vectors $\mathbf{D}_t$, $\mathbf{R}_t$, $\mathbf{S}_t$ or indirectly affect their values.

In the model (1)–(9), nodes can be dedicated real sources, storages or consumers of energy resources. However, most often they are aggregated groups of energy infrastructure facilities that have similar functionality, are fairly homogeneous in their characteristics or are spatially located in the same area. All nodes have geographical coordinates. As in the case of nodes, arcs can be real objects of transport, but in most cases they represent aggregated production capabilities for the transfer of energy resources. Intersystem connections between nodes of various energy systems represent the transformation of energy resources from one type to another.

### 2.2. Essential principles of creating a database of vulnerability indicators

When determining vulnerability indicators, the following principles of forming data storage structures are implemented:

1. Separate tables identical in structure are formed to store data on territorial units and territorial associations. The table with territorial associations can simultaneously include groups of territories at different levels (for example, federal districts and the country as a whole). Thus, identical storage of detailed and aggregated data by territories is ensured, and the procedures for their further processing are consistent.
2. The data in the generated tables should be identified by the study scenarios, territories or their associations. The composition of vulnerability indicators may vary. It is determined mainly by the goals and level of analysis.
3. The organization of data storage on vulnerability indicators should correspond to the following points:
   - the tables should contain absolute (limit and calculated) and relative values in order to preserve the possibility of assessing the vulnerability of objects from different points of view;
   - the determined indicators can be single (a specific technology of an object) and complex (a convolution of various technologies of objects). The level of complexity of indicators, the necessary formalization is implemented at the stage of determining absolute values. Relative values are determined at the absolute level, regulated by the type of analyzed technologies;
   - from a technological point of view, the tables must necessarily contain data on the availability of energy needs, additionally data on the intensity of use of the input part (extraction, production, storage), the intensity of the use of interchangeability opportunities (in relation to fuel) can be included. The type of technology determines the rules for determining relative values.

Vulnerability indicator tables constructed in accordance with the above principles form the necessary and sufficient information base for further quantitative assessment of vulnerability.

### 2.3. Evaluation of the energy infrastructure vulnerability

The perturbation scenario is a failure of $K$ elements of the energy infrastructure occurring during $T$ time periods [3]. The number of possible groups with multiplicity less than or equal to $K$ formed from $n$ pre-selected elements of the energy infrastructure is equal to

$$L = \sum_{k=1}^{K} \frac{n!}{(n-k)!k!}.$$

For practical reasons, $K$ should not exceed 3 or 4, as $L$ grows rapidly as $K$ grows. To compensate for this disadvantage and speed up the computational experiment, distributed computing can be used to assess the vulnerability of the energy infrastructure. The distributed perturbation generation algorithm [17] allows for each integer from the segment $[1, L]$ to determine the list of disconnected elements of the energy infrastructure corresponding to this number.

If, due to the absence or low reliability of available statistical data, it is impossible to determine the probability of accidental failure of an energy infrastructure object, then fuzzy logic is used to assess the risk of accidental failures. For each class of disturbances, risk factors (linguistic variables) are identified that determine the occurrence of this disturbance on a certain type of energy infrastructure objects. In turn, the risk factor is characterized by its parameters. Further, on the basis of the processed values of the risk factor parameters, membership functions related to the corresponding linguistic variable are constructed. Then a base of fuzzy rules is formed with many input variables (risk factors) and one output variable (the risk of accidental failure at a specific energy infrastructure facility).

According to the number of the disturbance and the given configuration of the energy infrastructure, the list of purposefully disabled elements is restored according to the above algorithm. For other infrastructure elements, the probability of accidental failure is determined, if possible. For these elements, multi-period random failures are then iteratively simulated using the Monte Carlo method. In the modelling process, a 128-bit congruent pseudorandom number generator is used, taking into account the specifics of parcel and distributed computing [18].

The combined consequences of directed attacks and random failures for any of $T$ time periods are calculated on the model (1)–(9). In each of the $N$ iterations of the Monte Carlo cycle, the consequences of the disturbance obtained for the last period $T$ are stored in the database.

The consequences of disturbances are loaded from the database, representing the values of the model parameters (1)–(9). Based on them, the values of the simple and integrated vulnerability indicators described above are calculated and stored in the same database. The calculation of the values of indicators, if necessary, can be carried out in a distributed manner.

Vulnerability assessment of energy infrastructure can be carried out in many different ways. In the analysis of the vulnerability of CI, such types of vulnerability assessment as a global vulnerability analysis and the search for critical elements are distinguished [14].

### 2.4. Global vulnerability analysis

Global analysis studies the vulnerability of CI as a system property. It is carried out by affecting the energy infrastructure with disturbances of a given class with an increasing amplitude of the impact, which is achieved, for example, by increasing the number of disconnected elements. As the magnitude of the impact of disturbances increases, the productivity of the CI decreases. If the performance drop occurs slowly, it is considered protected from the class of disturbances under consideration, if it is fast, then the CI is considered vulnerable to this class of disturbances. Thus, the result of a global vulnerability analysis is graphs of the dependencies of the drop in system performance on the number of disabled elements.

At the beginning of the global analysis, the most representative disturbance scenarios are selected. In these scenarios, compared to others, with the same number of failed elements, the size or scale of the negative consequences will be maximum. The size and scale of the consequences of disturbances is estimated by the values of vulnerability indicators stored in the database. Since the consequences of disturbances in terms of vulnerability indicators can be assessed in different ways, the problem of multi-criteria choice arises here. This problem can be solved by using the following known methods [19]:

- sequential comparison of variants of criteria values ordered according to their significance (lexicographic method);
- selection of options according to the largest number of criteria with the best values (majority method);

- Pareto-optimal choice.

The input parameters for these methods are the number of criteria, criteria optimality conditions, the number of variants of criteria values (integer scalar), variants of criteria values. At the output, a set of options is formed, selected according to the specified criteria and conditions of their optimality [20]. In this case, the criteria are vulnerability indicators, the variants of the criteria values will be the values of the indicators corresponding to the compared scenarios of disturbances, the optimality condition is the maximum.

Further, according to the values of vulnerability indicators for the most representative disturbance scenarios, graphs of the dependencies of the drop in system performance on the number of disabled elements are formed. These graphs are then used to compare different configurations of the energy infrastructure by vulnerability.

### 2.5. Search for critical elements

The search for critical elements explores the vulnerability of CI at the level of individual elements, that is, in the local sense. In the literature, there are many different measures of the importance of CI elements [21] that can be used in the search for critical elements. The choice of measures of importance directly depends on the points of view from which the simulated energy infrastructure is considered. In this case, such measures are vulnerability indicators and model variables (1)–(9) stored in the database.

For example, if the perturbation scenario is $j = 1, \dots, L$ consists in purposefully disabling only one element out of $n$, then the importance of this element can be assessed from the side of the risk of under-supply of energy resources to end consumers as follows [22]:

$$RA_j(W) = P_j(W) - P_0(W),$$

where $W$ — the vector whose element values in percentages set the level of under-supply of certain types of energy resources to various categories of consumers; $P_j$ — the probability of under-supply of energy resources of level $W$ during the implementation of the disturbance scenario $j$; $P_0$ — the probability of under-supply of energy resources of level $W$ in the normal state of the energy infrastructure or the baseline scenario $j = 0$.

The probability of under-supply of energy resources of level $W$ for the disturbance scenario $j = 1, \dots, L$ is calculated as follows:

$$P_j(W) = \frac{1}{N} \sum_{i=1}^{N} F(W),$$

where $F$ — a function that iterates $i = 1, \dots, N$ of the Monte Carlo cycle is equal to 1 when the condition $\mathbf{z}_T^i \leq \frac{W}{100}\mathbf{R}_T^i$ is true and 0 otherwise, $\mathbf{R}_T^i$ — the vector of needs for certain types of energy resources for various categories of consumers in the last time period $T$ of the perturbation scenario at iteration $i$ of the Monte Carlo cycle, $\mathbf{z}_T^i$ — the vector of under-supplies of certain types of energy resources to various categories of consumers in the time period $T$ at iteration $i$ of the Monte Carlo cycle.

There may be several levels of undersupply of energy resources $W$, and each of them will correspond to its own list of critical elements of energy infrastructure. Since these lists may not coincide with each other, the problem of multi-criteria selection arises during the final approval of the lists, which is solved using the methods listed above.

## Conclusion

This article proposes a methodology for quantifying the vulnerability of energy infrastructure, consisting of the following stages:

- Setting parameters of disturbance scenarios, including the territorial and production structure of individual energy systems and the connections between them, socio-economic conditions of functioning and natural and climatic factors.
- Conducting calculations on which targeted attacks on the energy infrastructure and accidental failures of its elements are modelled using the Monte Carlo method.
- Processing of calculation results, where vulnerability indicators are calculated for the entire set of disturbance scenarios based on their consequences stored in the database.
- Analysis of calculation results.

At the last stage, discrete multi-criteria selection algorithms are used to determine the most important elements of the energy infrastructure. Also, with the help of these algorithms, graphs of the drop in system performance are formed, according to which various configurations of the energy infrastructure are compared by vulnerability.

The concept of risk is used twice in the methodology of quantitative vulnerability assessment. In the first case, the risk of accidental failure of the element is estimated on the basis of statistical data or, in their absence or low reliability, using fuzzy logic. In the second case, when the elements are determined, the complete failure of which creates the highest risk of under-supply of certain types of energy resources for various categories of consumers.

Thus, in the process of carrying out this work, the authors, within the framework of a new approach to the comprehensive analysis of vulnerability, developed a methodology for its quantitative assessment, which:

- uses previously implemented algorithms of discrete multi-criteria selection to find options for the functioning of the energy infrastructure that are optimal in terms of survivability;
- performs processing, storage and analysis of natural-climatic and socio-economic data for monitoring the processes of functioning of energy infrastructure facilities.

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ИНФОРМАЦИОННЫЕ ТЕХНОЛОГИИ

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## Комплексный анализ уязвимости мультиэнергетической системы

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### Аннотация

Предложена многоэтапная схема комплексного анализа уязвимости энергетической инфраструктуры. Схема использует реализованные ранее алгоритмы дискретного многокритериального отбора для поиска оптимальных вариантов функционирования энергетической инфраструктуры. Также осуществляет обработку, хранение и анализ природно-климатических и социально-экономических данных для мониторинга процессов функционирования объектов исследуемой энергетической инфраструктуры.

*Ключевые слова:* критические инфраструктуры, отказоустойчивость, анализ уязвимости, многокритериальный выбор.

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