RESOURCE ANALYSIS OF METHODS FOR ASSESSING THE DEPENDABILITY OF POWER SUPPLY SYSTEMS IN CONDITIONS OF NEGATIVE IMPACTS

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Abstract: The article aims to analyse existing methods for assessing the reliability and dependability of power supply systems in the event of partial or complete failure of such systems. The basis for the analysis is the resources that must be spent to perform dependability assessments, such as the complexity of calculations, the amount of initial data required to assess the reliability of complex electrical systems and time costs. Resource analysis was performed for the deterministic methods of system modelling, the Markov analysis method, and the Monte Carlo method. Based on the analysis, a conclusion was drawn about the feasibility of using Markov analysis for assessing the dependability of complex power supply systems. A list of possible events from external negative impacts on power supply systems' generating and distribution capacities was developed and substantiated for use in Markov analysis.

Key words: dependability, dependable energy supply, power grid reliability, power supply systems, Markov analysis, Monte Carlo method.

1. INTRODUCTION

The missile strikes carried out on country's energy infrastructure revealed systemic shortcomings in the construction of the entire energy sector related to the generation, transmission, and consumption of electricity.

As the situation in Ukraine has shown, a significant problem is the power supply system's insufficient resistance to destructive influences and relatively low maintainability. The issue of creating reliable electrical systems for the generation and distribution of electric energy, resistant to destructive influences of man-made or natural origin, remains unresolved.

Under the dependability, we will understand the property of the system to ensure the continuous and reliable supply of electricity to consumers under given operating conditions, including the possibility of recovery after failures or damage. Dependability is a broader concept than reliability. It covers the entire complex of system properties necessary for its effective operation, while reliability is its main part, which concerns failure-free operation.

Power systems worldwide are built on the same principle—generating capacities are geographically tied to natural resources, and the number of generators is relatively small. Power transmission lines with a system of transformer substations transport electrical energy to distributed consumers.

As the experience of military operations in Ukraine has shown, such a system design is vulnerable to attack, and its reliability is at a very low level. Moreover, such a reduced level of reliability is inherent not only to the Ukrainian energy system but also to energy systems worldwide.

The most rational way to increase the reliability of power supply systems is to change the existing paradigm of their construction by creating and implementing distributed generation systems.

Thus, in the article [1] the authors proposed the concept of creating dependable power supply systems that can maintain their operability even in the event of partial or complete destruction of any of their parts. This concept is based on the use of distributed generation instead of traditional centralized generation.

Thus, the reliability and dependability of power supply systems are key parameters for their effective operation, especially in conditions of unforeseen destruction caused by natural disasters, man-made accidents or human factors. Analysing these parameters allows us to assess the ability of the system to ensure an uninterrupted power supply even in crises. The purpose of this article is a comparative analysis of the main methods for studying the reliability and dependability of power supply systems, with a special emphasis on their advantages and limitations.

2. RELATED WORKS

The problem of increasing the reliability of power supply systems is relatively new. Thus, the first mention of reliability in the context of power supply found by the authors dates back to 1993 [2]. In this article, the authors say that improving the quality of power supply while simultaneously controlling costs is an ambitious goal and propose a new approach to analysing and considering reliability indicators, which is based on a combination of cost analysis and reliability assessments. The methods proposed in this work are designed to adapt to the specific features of medium-voltage switchgear only.

In a very detailed book [3], published three years later, the authors consider the theory of reliability of technical systems as applied to power supply systems. This book includes a dedicated chapter on distributed generation systems. In particular, the authors talk about two disadvantages of traditional generating systems. First, generating stations are individually very capital-intensive, and second, the cessation of generation can have large-scale catastrophic consequences for both society and the environment. However, the book does not pay attention to the reliability of distribution networks.

The Monte Carlo method can be used to assess the ability of the generating part to satisfy the total demand for the generation volume of the power supply system [4]. This paper describes in detail the mathematical side of this method and gives recommendations for its application in the power industry. The authors note that Monte Carlo modelling can be considered better than the analytical approach in situations where it is necessary to analyse a very large set of system states. At the same time, the authors note that the assessment of the reliability of distribution systems is significantly different from the principles of system analysis applied to generation systems or the power supply system as a whole. The impact of distributed generation on the reliability of power systems is studied in [5]. The authors of this article propose models that take into account the integration of distributed energy sources and their impact on the overall reliability of the system. The concept of using a probabilistic reliability model to calculate the equivalence of a distributed generation facility to a conventional distribution facility in a deregulated power industry environment is noteworthy. The methods developed in the article do not allow us to assess the reliability of the entire system as a whole. At the same time, the authors rightly point out that despite the initial costs, the implementation of distributed generation systems is an effective solution to the problem of uninterrupted power supply in the future. Both suppliers and consumers of electricity benefit.

Fuzzy logic methods can be used to assess the reliability of power supply systems. Thus, in the article [6], a modernization of the existing fuzzy logic method for assessing the reliability of electrical substations with implemented distributed generation is presented, taking into account the uncertainty and inaccuracy of input data. It is indicated that the method gives satisfactory results from an engineering point of view and provides a high level of accuracy and simplicity of the model. The conclusions of the article state that the fuzzy logic method can be used to assess the reliability of electrical substations with distributed energy sources. However, the number of resources required for its use is not given in the article.

A hybrid method for assessing the reliability of microgrids is proposed in [7]. In this paper, Monte Carlo simulation is combined with the analytical method. A microgrid is a separate, relatively autonomous element of the overall distributed generation network. The sensitivity analysis conducted in the article on the consequences of a failure of an individual microgrid for the higher-level network is noteworthy.

Special attention is paid to the article [8], which attempts to optimize the reliability of electrical power distribution systems. For this purpose, the article develops a network model and an algorithm for calculating reliability, which is suitable for multi-criteria network analysis. The proposed algorithm for calculating reliability and outage costs is based on Monte Carlo simulation and a genetic algorithm. However, a significant drawback of the algorithm is its focus only on optimizing the power circuit breaker distribution system, which significantly narrows the scope of application.

A comprehensive and systematic review of achievements in power system maintenance and their significance for the field of power system reliability is given in [9]. This work systematizes literary sources and analyses the most significant stages in the context of power system adequacy and safety improvement. The article develops a taxonomy of various strategies for the technical maintenance of electrical power equipment. The article contains a review of 30 literary sources since 1995, which confirms the comprehensiveness and completeness of the review.

In the context of a review of methods and approaches to assessing the reliability of power supply systems, the article deserves special attention [10] deserves special attention. It was published in the same year as the article [9], but this article contains 50 references. The main value of this work is that it systematizes methods for assessing the reliability and dependability of power supply systems. However, the computational complexity and resources for their use are not given for all methods. This is the main drawback of this article.

Based on the review's results, the following interim conclusions can be drawn. First, the problem of assessing the dependability and reliability of power supply systems is relevant, as evidenced by many scientific publications related to this topic. Second, the literature does not recommend any specific method for performing such an assessment. This indicates the need for additional analysis of existing methods for assessing power supply systems.

3. ANALYSIS OF METHODS FOR ASSESSING THE DEPENDABILITY OF POWER SUPPLY SYSTEMS

The assessment of the reliability and dependability of power supply systems depends not only on the accuracy of the methods but also on the computational resources they require. As resources, we will use the computational complexity of these methods, the amount of time it takes to calculate the dependability indicators, and the amount of initial data. Below is a detailed analysis taking into account these three resource factors.

3.1. Deterministic methods

Deterministic methods for assessing the reliability of power supply systems are based on determining the indicators of reliability, dependability, continuity and other system characteristics, based on deterministic (precisely known) parameters and operating scenarios. These methods are based on mathematical models that take into account fixed initial data and assumptions, regardless of probabilistic (stochastic) factors. Modelling is carried out using specialized software, for example, MATLAB [11]. The advantages of these methods are: ease of implementation – the method usually does not require complex software or large computing power and low computational cost. Calculation execution time is also minimal [12].

The shortcomings that are most fully substantiated in [13] include: the lack of a probabilistic component. These methods do not take into account random events, so their suitability for our study's needs is very low. It is impossible to take into account complex interdependencies or dynamic changes in system states. A serious disadvantage is also minimal scalability. These methods are not suitable for large or complex systems.

The resources required for using deterministic methods are as follows [14] :

- Computing resources: low.
- Data: requires precise fixed component parameters.
- Time: short simulation time.

The areas of application of deterministic methods are the initial analysis of simple systems, as well as their use in conditions where resources for complex modelling are insufficient.

3.2. Probabilistic methods

Probabilistic methods are based on the analysis of statistical data on the probability of component failure and time to failure. Such methods include, for example, Failure Modes and Effects Analysis (FMEA) [15], deep learning methods [16], Fault Tree

Analysis (FTA) [17], and others. They use such indicators as MTTF, MTTR, and the probability of failure-free operation [18]. The advantages of these methods are as follows: the ability to account for random events. the ability to use real data, which increases the accuracy of estimates, and also probabilistic methods are suitable for systems of medium complexity.

At the same time, they have significant disadvantages that make their use difficult for power supply systems with complex configurations: dependence on statistical data because in the absence of reliable data, the accuracy of warranty estimates is significantly reduced. These methods have limited capabilities for modelling complex dynamic systems.

Resource:

- Computing resources: medium (use of specialized software).
- Data: long-term failure history and system parameters are required.
- Time: depends on the volume of statistical data but is usually moderate.

Areas of application

- Analysis of systems with a small number of components or weak dependencies between them.
- Assessment of general reliability characteristics.

3.3. Markov analysis

This method is based on modelling the system's states and the probabilities of transitions between them. It takes into account both failures and the possibility of component recovery [19].

The advantages and disadvantages of using Markov analysis are described in detail in [20]. The advantages are: first of all, this is the possibility of dynamic modelling. Secondly, Markov analysis ensures high accuracy of the result. It takes into account complex interdependencies between system elements. Flexibility. It is suitable for systems of any complexity. And thirdly, modelling allows us to take into account rare events.

Markov analysis has its drawbacks. First of all, it is highly complex. Building models require special knowledge of the object being studied. In addition, it is computationally expensive. Analysis of complex systems requires powerful computers or servers. Finally, accurate data is required for analysis. The inaccuracy of the initial data can significantly affect the results.

Resources, the analysis of which is fully presented in [21]:

- Computing resources: high (use of servers or clusters for modelling).
- Data: comprehensive details about system parameters and the probabilities of state transitions.
- Time: significant for preparing models and performing calculations.

Areas of application

- Analysis of complex systems with numerous interconnected components and states.
- Assessment of system behaviour under conditions of unforeseen destruction.

3.4. Monte Carlo method

This iterative method employs multiple simulations of random scenarios to estimate reliability parameters statistically [22]. The article [23] provides a detailed analysis of the advantages and disadvantages. It describes the application of the Monte Carlo method and Markov analysis to dynamic biological systems, but the conclusions of this analysis can be extended to all dynamic systems. The advantages of this method are: its flexibility and capability of accounting for a wide range of factors, including accidental destruction; independence from the form of distribution and its ability to simulate non-standard scenarios. These methods can be applied to systems with different characteristics.

Disadvantages are: high computational cost, long execution time and inaccuracy in rare scenarios. Modelling such events requires even more iterations.

Resource

- Computing resources: high (servers, clusters or supercomputers).
- Data: flexible input requirements depending on the level of detail of the model.
- Time: significant, especially for complex systems with a large number of components.

The scope of application includes the analysis of complex systems where deterministic or analytical methods cannot be applied and the assessment of scenarios with high uncertainty.

4. RESULTS OF ANALYZING

Table 1 summarizes the comparative analysis results. It does not provide absolute indicators, as they depend greatly on the type and complexity of the system being analysed. However, it allows for the selection of a method for assessing the reliability of power supply systems.

Table 1. Results of comparative analysis

Methods	***Computing resources***	***Data requirements***	***Execution time***	***Precision***
Deterministic	*Low*	*Low*	*Low*	*Low*
Probabilistic	*Medium*	*Medium*	*Average*	*Limited*
Markov analysis	*High*	*High*	*High*	*High*
Monte Carlo	*High*	*Flexible*	*Very high*	*High*

This table demonstrates that deterministic methods are characterized by the lowest demands on resources, time, and data. However, these methods are not suitable for evaluating the reliability of power supply systems under adverse conditions. This limitation arises primarily from the need for complex mathematical models to describe the system's operating states in terms of currents, voltages, or transmitted power. Consequently, deterministic methods are constrained in their ability to analyse complex scenarios involving negative impacts on the system, which leads to reduced accuracy. Probabilistic methods provide an average balance between resources, data requirements and accuracy. It is suitable for performing analysis under negative impacts precisely because of the probabilistic nature of these impacts. However, these methods are practically unable to take into account the development of the consequences of these negative impacts over time, which is why the accuracy of the analysis of real power supply systems is low.

Markov analysis is the most accurate method for dynamic systems with a high level of detail. It was developed for systems where it is important to take into account transient states and time dependencies, which is a significant advantage for analysing the development of the consequences of negative impacts. However, to use this method, it is necessary to carry out painstaking work on estimating the probabilities of transitions between states. Given the complexity of power supply systems, the number of states can be very large. In addition, these probabilities are not defined in most cases, which requires the use of the expert assessment method. Therefore, when using Markov analysis, it is necessary to develop methods for reducing the number of system states.

The Monte Carlo method is the most flexible method that can simulate any scenario. It is very accurate, but due to its high resource and time requirements, it cannot be recommended for reliability assessments of complex power supply systems.

In addition, all of the listed methods are not aimed at the analysis of dependability. But as already mentioned, dependability is a complex criterion in which reliability plays a significant role. Other components of dependability, such as uptime, and mean time to failure, can be calculated through the probability of failures. Therefore, when analysing dependability, reliability calculation methods can be used.

Thus, when assessing the reliability of power supply systems, preference should be given to the Markov analysis method. However, this analysis requires minimizing the system of states in which the system may be under negative influences.

5. SELECTION OF SYSTEM STATES FOR MARKOV ANALYSIS

The selection of a state system for Markov analysis is guided by the necessity to balance accuracy, data dependability, and practical feasibility. The following criteria were used to select states for Markov analysis: level of detail, data dependability, system complexity, computational resources, and practical significance.

The level of detail of the criteria depends on the purpose of the modelling: whether it is necessary to investigate the overall level of reliability of the system, or to analyse individual intermediate states. For a quick assessment of the overall functioning, a smaller number of criteria is sufficient, while for a detailed analysis of the degradation of the system, additional states must be introduced.

Data dependability means the dependability of data on the probabilities of transitions between states and the failure rates of components. This data can be taken from technical documentation, accumulated failure detection dynamics, and obtained data on the behaviour of the system under external negative influences. When data is limited, a simplified model with fewer states is preferable.

The system's complexity includes the number of components, their types and relationships. In complex systems, which include power supply systems, it is advisable to reduce the number of states to assess the reliability, since with the complexity of the system and with an increase in the number of states, the complexity of the analysis increases significantly.

The need for computational resources also increases with the complexity of the system and the number of states to be analysed. For systems with numerous components, adding states may become impractical due to memory and computational time constraints.

Practical significance determines whether the additional states are important for decision-making. If the analysis results remain almost unchanged when the model is simplified, the unnecessary states can be eliminated. For example, for systems where small degradations do not significantly affect their functioning, one can limit oneself to three states.

Therefore, to perform dependability assessments of power supply systems that have a complex branched structure with a significant number of nodes, it is appropriate for Markov analysis to consider only three states, which are conventionally designated as "100%", "50%" and "0%. The state "100%" corresponds to full system performance, "50%" to partial degradation, and "0%" to complete failure. These states cover the main stages of system operation, which are often the most important for engineers.

Considering only three states strikes a balance between accuracy and complexity, significantly reducing model complexity compared to more detailed approaches (e.g., 4 or 5 states). This is important for the analysis of large systems, where the number of states increases exponentially as new components are added.

6. CONCLUSION

Thus, the analysis conducted allows us to draw the following conclusions.

Markov analysis and Monte Carlo simulation are the most accurate and flexible methods for assessing the reliability of power systems under unpredictable disturbances. However, despite its reliance on detailed data, Markov analysis provides a balanced approach between computational complexity and time efficiency. Its ability to model dynamic processes and provide accurate reliability estimates makes it the preferred choice for analysing complex power systems. Deterministic and probabilistic methods remain useful for approximate estimates or analysis of simple systems.

It is proposed to conduct Markov analysis using three system states, striking a balance between analysis accuracy and complexity.

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