UDC 621.311
DOI: 10.15587/1729-4061.2025.322920

DEVELOPMENT OF A METHOD FOR RELIABILITY ASSESSMENT OF DISTRIBUTION POWER NETWORKS UP TO 110 kV

Fariza Abilzhanova
Corresponding author
Master of Engineering Sciences, PhD Student
Department of Energy Systems*
E-mail: fariz-90@mail.ru
Felix Bulatbaev
Candidate of Technical Sciences, Associate Professor
Department of Energy Systems*
Aizada Kuanyshtaeva
PhD Student
Department of Automation of Production Processes*
*Abylkas Saginov Karaganda Technical University
N. Nazarbayev ave., 56, Karaganda,
Republic of Kazakhstan, 100027

The study focuses on the reliability assessment of distribution power networks operating at voltages up to 110 kV, addressing the challenges of increasing loads, aging infrastructure, and the integration of renewable energy sources. A novel method and model for reliability assessment are proposed, incorporating failure rates, recovery times, and topological characteristics of networks. The research identifies critical factors influencing network reliability, including the level of redundancy, operational conditions, and climatic impacts. Notable findings show that network points with multiple feeder connections demonstrate the highest reliability, exceeding 99.99 %, while those with single-transformer configurations are the most vulnerable to failures. The average failure rate for overhead lines is calculated at 1.29 failures per 100 km annually, with recovery times reaching up to 40 hours for critical nodes.

The results are explained by the interplay of structural and operational factors, where redundancy significantly enhances reliability, and outdated equipment increases vulnerability. The study's distinguishing feature lies in its use of Markov processes to dynamically model failures and recoveries, offering a comprehensive framework compared to traditional static methods. The practical applications of the results include improving network design through enhanced redundancy, optimizing maintenance strategies for critical elements, and supporting the integration of Smart Grid technologies. These findings contribute to the development of more resilient and efficient power distribution networks, adaptable to modern operational demands

Keywords: distribution networks, power reliability, Markov processes, redundancy assessment, failure rate

Received 04.12.2024
Received in revised form 27.01.2025
Accepted 11.02.2025
Published 28.02.2025

How to Cite: *Abilzhanova, F., Bulatbaev, F., Kuanyshtaeva, A. (2025). Development of a method for reliability assessment of distribution power networks up to 110 kV. Eastern-European Journal of Enterprise Technologies, 1 (8 (133)), 15–23. https://doi.org/10.15587/1729-4061.2025.322920*

1. Introduction

Ensuring the reliability of electricity distribution networks is one of the key challenges of the modern energy sector. Increasing energy consumption, the integration of renewable energy sources (RES), digitalization of power systems and climate change place additional demands on the reliability of distribution networks.

In recent decades, there has been a rapid increase in the number of grid-connected devices, including Smart Grid and distributed generation elements. These changes significantly increase the complexity of grid management and the probability of failures. In Kazakhstan, the share of outdated electrical infrastructure has reached critical levels. According to official reports from the Ministry of Energy of the Republic of Kazakhstan [1], approximately 70 % of power grid equipment has exceeded its normative service life, leading to a higher frequency of failures and increased operational costs. Additionally, the failure rate for overhead lines in Kazakhstan is estimated at 1.29 failures per 100 km annually, with an average recovery time of up to 40 hours for critical nodes [2]. The slow pace of modernization further exacerbates these challenges, with only 3–4 % of the grid infrastructure being upgraded annually [3], limiting the ability to ensure stable electricity supply.

The integration of renewable energy sources, such as solar panels and wind turbines, brings additional challenges. Generation from renewable energy sources is characterized by a high degree of variability, which makes it difficult to manage power distribution and increases loads on grid elements. These circumstances require adaptive control methods to take into account the dynamic state of the grid and ensure its stability under variable operating conditions.

Climatic changes also have a significant impact on the reliability of power systems. Extreme weather conditions in Astana city – strong winds, icing, thunderstorm overvoltage – contribute to damage of power lines and other equipment. To improve the stability of networks, research is required to develop new materials, technologies and design solutions that can withstand aggressive climatic influences.

In conditions of limited resources for modernization and maintenance of infrastructure, the application of intelligent technologies is of particular importance. The development of failure prediction methods based on machine learning and big data analysis can significantly reduce the probability of accidents and optimize maintenance schedules. In addition, the digitalization of power systems opens up opportunities to automate diagnostics, monitor equipment condition and control energy flows in real time.

Consequently, the need for research in the field of reliability improvement of distribution grids is driven by a number of factors: ageing infrastructure, increasing loads, integration of renewable energy sources, changing climatic conditions and the transition to digital technologies. The results of such studies are of high practical significance, as they allow not only to minimize the risk of accidents, but also to ensure the sustainable development of power systems that meet current and future requirements. Therefore, studies that focus on improving grid reliability have scientific relevance.

2. Literature review and problem statement

In [1], the authors investigate important aspects of integrating renewable energy sources (RES) into distribution network structures. The specific challenges that arise when connecting renewable energy sources, including technology compatibility and performance evaluation issues, are addressed. The attributes of various hybrid systems including solar, wind, storage and biomass are analyzed in detail, as well as their integration with combined heat and power systems. However, the authors highlight the difficulties associated with the limited capacity of existing grids to handle variable RES generation. They emphasize the lack of modern technologies that allow efficient management of distributed generation and real-time monitoring of system status.

Reliability issues are also related to equipment wear and tear, insufficient maintenance and operation under increasing loads. Aging infrastructure, complex operating modes and insufficient flexibility of existing grid management practices are the main reasons for increased accident rates and decreased grid efficiency. The study of distribution grid reliability requires consideration of various factors, including the effect of partial discharges on insulation elements. In this regard, the approach presented in the article [2], where theoretical and experimental studies of leakage currents on suspended insulators of high-voltage transmission lines are carried out, is relevant

When assessing the reliability of electrical distribution networks, it is important to consider energy efficiency approaches that can be adapted to analyses and upgrade network components. For example, a paper proposing a rapid method for analyzing LED luminaires presents a practical formula for engineering luminous flux estimation, highlighting the importance of affordable and efficient rapid equipment parameter estimation tools applicable to both power engineering and related fields [3].

In [4], the impacts of distributed generation (DG) on medium and low voltage distribution networks are investigated and approaches are developed to improve their performance. DG interconnection, load coordination and the application of different control strategies for scheduling and optimizing network performance are considered. The literature covers a wide range of issues including load management, distribution network planning, acceptance capacity assessment and energy utilization improvement. This indicates a comprehensive approach to the problem. However, the paper does not provide information on specific findings and results of the study, such as indicators of improved stability, flexibility or energy utilization factor.

In [5], a study on line failures in power grid transmission systems explores the use of computational tools and a linear power flow model. The research focuses on developing metrics for network stability assessment and an algorithm for identifying cascading faults and their mitigation. The proposed approach utilizes a pseudo-inverse matrix (Moore-Penrose) and impedance analysis. However, the study lacks quantitative validation, such as specific numerical results or case studies that demonstrate the effectiveness of the proposed method. Additionally, the description of the cascading fault identification algorithm does not include details about its structure or comparative advantages, making it difficult to assess its practical applicability.

In [6], the relationship between climatic conditions, maintenance strategies and reliability indicators of electricity distribution networks was investigated. Using statistical modelling, the failure rate and recovery time of equipment considered as independent parameters for different groups of weather events were analyzed. Based on the obtained model, the efficiency of different approaches to preventive maintenance was compared.

Reliability assessment of distribution power grids requires the consideration of various factors, including the integration of renewable energy sources. The paper [7] presents approaches for predicting wind characteristics in urban environments, which can be useful for the design and operation of grids connecting wind energy facilities.

[8] the study aims to address the reliability of DC switches, which is important for the development of DC grids. The application of the model for condition analysis and failure prediction emphasizes the mathematical rigor of the approach. The method allows finding weak links and analyzing for reliability improvement through redundancy. However, what is missing is how exactly the reliability indices were calculated and what structures were compared to. There is no indication of quantitative results or specific improvements achieved using the method.

In [9], the paper shows that existing algorithms for back-up protection against breaker failure are insufficient to detect partial failures, such as the failure of a single module of circuit breakers with modular structure. A back-up protection algorithm is proposed that quickly detects DC breaker failure based on the estimation of the counter-voltage generated by the energy absorption branch during the interruption.

In [10], state-of-the-art predictive maintenance strategies for transformers in electrical networks are utilized by applying deep learning techniques such as CNN and RNN. This is a significant contribution to improve the reliability and efficiency of power systems. However, no performance metrics (e.g., accuracy, F1-score) or measures of improvement over traditional approaches are given.

To improve the level of safety and reliability in distribution networks, the authors of [9] propose to implement the function of predicting emergency situations in digital protective relays. The proposal is based on the use of modern data processing methods, such as machine learning and big data analysis, which allows protective devices to predict the probability of emergency situations based on the analysis of current and historical parameters of network operation. This predictive function facilitates early detection of signs of equipment deterioration, unstable network modes and anomalies, which ensures timely preventive measures to avoid outages.

In [11], predictive digital relays are able not only to perform standard protection functions, but also to analyze the dynamics of changes in the network, adapting their settings to changing operating conditions. This improves the overall reliability of electricity supply and minimizes the risks of power outages, especially in the context of load growth and renewable energy integration. The deployment of such technologies represents an important step towards the next generation of smart distribution networks.

When evaluating the reliability of distribution power grids, particular attention is given to the diagnostics, monitoring, and assessment of critical power system elements, such as power transformers, which are essential for transmission and distribution. Key aspects of this review include the establishment of data acceptability criteria, selection of evidence sources, and analysis of results through summary charts and tables. Additionally, modern data analysis methodologies have been applied to enhance failure prediction and support decision-making processes in transformer asset management, contributing to the improvement of power system reliability [12].

Based on the reviewed literature, several unresolved problems emerge. Despite the extensive research on reliability assessment, most studies focus on isolated aspects such as predictive maintenance, failure detection, and integration of distributed generation, without providing a comprehensive framework for improving the resilience of distribution networks under real-world conditions. Moreover, the limited capacity of existing grids, aging infrastructure, and inadequate technological advancements in real-time monitoring and adaptive control methods remain major challenges.

Additionally, while various methodologies such as Markov processes, impedance analysis, and deep learning models have been proposed, none of them integrate multiple factors including grid topology, climatic conditions, and redundancy planning into a unified approach. The lack of quantitative validation and case studies further limits the practical applicability of these methods.

These gaps highlight the need for a systematic reliability assessment method that incorporates multiple influencing factors, integrates predictive analytics with real-time monitoring, and ensures adaptability to various network configurations. This research aims to address these challenges by developing a comprehensive method for evaluating and enhancing the reliability of distribution power networks, ensuring greater stability and resilience in modern electrical grids.

3. The aim and objectives of the study

The aim of this research is to develop a method for reliability assessment of distribution electric networks up to 110 kV, allowing to increase the stability and reliability of power systems by effectively analyzing the nodes, branches and structural features of networks.

To achieve this aim, the following objectives are accomplished:

– to investigate the factors influencing the reliability of networks, including technical parameters of equipment, operating conditions and the impact of external factors;

– develop computational techniques to enhance the accuracy of reliability calculations and ensure applicability to various network configurations.

4. Materials and methods

The object of the study is distribution electric networks with voltages up to 110 kV, their reliability, fault tolerance, and the influence of various factors such as equipment wear, climatic conditions, and the integration of renewable energy sources.

The main research hypothesis is that the development and application of a new reliability assessment methodology, considering the structural features of the network, failure rates, and recovery times, will enhance the stability and reliability of distribution electric networks. In particular, the use of Markov processes and the Newton-Raphson method is expected to enable more accurate modeling of failures and recoveries, as well as the identification of critical network nodes.

Assumptions made in the study are:

– failure and recovery rates follow an exponential distribution, which simplifies the modeling process but may not fully capture the effects of equipment aging and variable operating conditions;

– all network nodes are considered independent in terms of failure and recovery events, which helps streamline reliability calculations but may not account for interdependencies in real-world scenarios;

– the study focuses on distribution networks up to 110 kV, meaning that the findings may require adaptation when applied to higher voltage networks or systems with a high penetration of renewable energy sources;

– the network topology is assumed to remain relatively unchanged, with no significant reconfigurations during the analysis, despite the potential for dynamic changes in practical applications;

– environmental and climatic factors are treated as fixed parameters, meaning that their long-term variations and extreme weather conditions are not dynamically modeled;

– Markov processes are used for failure and recovery modeling, assuming that transitions between states depend only on the current state (memoryless property), which simplifies calculations but does not account for long-term degradation trends;

– the Newton-Raphson method is applied under the assumption that initial approximations are reasonably accurate, ensuring fast convergence, though in real applications, poor initial conditions may lead to errors;

– the study assumes that network components operate under nominal conditions, without considering nonlinear effects such as sudden load fluctuations, voltage instability, or emergency switching events.

Simplifications adopted in the study are:

– use of equivalent circuit models and network topology simplifications to reduce computational complexity while maintaining accuracy in reliability assessments;

– application of Markov processes under the assumption of a memoryless property, simplifying the modeling of failures and recoveries but not accounting for long-term degradation trends;

– assumption of constant failure rates and recovery times, based on historical data, without considering potential nonlinear variations due to operational stress or environmental changes;

– neglecting the impact of sudden load fluctuations and extreme weather events, which may influence system performance but are not explicitly modeled in this study;

– use of the Newton-Raphson method for power flow calculations, assuming that the initial approximations are sufficiently accurate to ensure convergence, while real-world scenarios may present challenges with poor initial conditions;

– exclusion of emergency switching operations and cascading failures, focusing instead on steady-state reliability analysis.

The Markov process-based method is an effective approach for modelling and analyzing the reliability of electricity distribution networks. It describes system behavior over time as a sequence of random events, where state transitions occur either discretely or continuously [13].

A key property of Markov processes is memory lessens, meaning that the probability of transitioning to a new state depends only on the current state, not past events. This simplifies the mathematical representation of complex systems, such as power networks, where failures and recoveries continuously alter operational conditions.

The model assumes that failure and recovery processes follow an exponential distribution, enabling the application of probabilistic reliability assessment methods. This approach is particularly valuable for long-term network stability evaluation, as it allows for the quantification of system state probabilities and eliminates the need for computationally intensive simulations:

$$f(t)=\lambda\cdot e^{-\lambda t}, \tag{1}$$

the model assumes that all events, such as failures and restorations, occur at a constant intensity, which may not always reflect the real dynamics of the power system, where failure rates may depend on operating conditions, equipment age and other factors. This limitation should be taken into account when interpreting the calculation results.

The analytical method based on the Bernoulli scheme has been widely used. According to this scheme, a series of independent tests are conducted, where each test ends either with success with probability p or failure with probability of failure $q=1-p$ [14].

For this scheme, i can calculated the probability that out of n trials, k will end in success and $(n-k)$ will end in failure:

$$P_k\left(n\right)=C_n^k p^k q^{n-k}, \tag{2}$$

where:

$$C_n^k=\frac{n!}{k!\left(n-k\right)!},$$

C_n^k – binominal coefficient also known as the "number of combinations"; $n!$ – factorial of the number n which is equal to the product of all natural numbers from 1 to n; $k!$ – factorial of the number k; $(n-k)!$ – factorial of the difference $n-k$.

Creating a model that takes into account the dynamic nature of the network will require not only a revision of existing methodologies, but also the development of a new concept of reliability. Such a model must account for changing network parameters in real time, predict likely failures, and automatically adjust protection systems to current conditions. This also includes updating reliability assessment methods so that they can work effectively in networks with distributed generation and intelligent components.

The use of iterative methods, such as the approach of simple iterations, can greatly simplify the solution of linear systems of equations used in reliability calculations. This procedure allows for consistent refinement of variable values and ensures that they are similar to the true solution. Although this method has relatively low efficiency compared to more advanced algorithms, it remains useful for problems where ease of implementation and low computational cost are important:

$$Ax=b, \tag{3}$$

$$x=Bx+c, \tag{4}$$

$$x^{n+1}B''+c, \tag{5}$$

$$x=x-D(Ax-b). \tag{6}$$

Any system can be represented in the form (4) and provided that det $D\neq 0$, it is equivalent to system (3). At the same time, any system (3) equivalent to (3) can be written in the form (5), where the matrix:

$$D=(E-B)A^{-1}.$$

According to the sufficient condition theorem of convergence, the method of simple iteration is stable and converges to the only solution if certain conditions are fulfilled, where the method of simple iteration guarantees the uniqueness of the solution of the system of equations (4) provided that the norm of the matrix $||B||<1$. In this case, the iterative process described by equation (5) will converge to the correct solution with geometric speed, providing a gradual reduction of the error at each step of the process.

The Seidel method is known for its simplicity and computational efficiency, refining variable values sequentially within a single iteration. This approach minimizes memory usage and simplifies implementation, making it suitable for small to medium-sized problems where system structures are relatively simple. However, its effectiveness decreases in highly nonlinear or complex network topologies.

In contrast, Newton's method offers higher accuracy and faster convergence, particularly beneficial for solving complex nonlinear systems, such as electrical networks with variable parameters. However, it is highly sensitive to initial approximations-poor initial values may lead to divergence or incorrect solutions.

The Backward/Forward Sweep Method is widely applied in radial power grids, including networks with distributed generation. It consists of two phases:

– backward sweep – starting from peripheral nodes to compute branch currents toward power sources;

– forward sweep – determining voltage distribution by recalculating values from power sources outward.

This two-stage structure enhances calculation accuracy and adaptability, making it a valuable tool for load flow analysis under variable operating conditions and for optimizing small-scale distributed generation systems [15].

This Fig. 1, 2 labeled Direct/Backward method illustration, depicts two configurations of power supply connections in a distribution network.

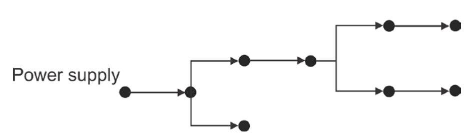

Fig. 1. Direct method illustration

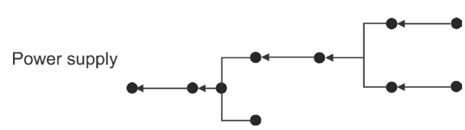

Fig. 2. Backward method illustration

The two configurations are:

– Fig. 1. Direct method illustration. Straight running: the power flows directly from the source to the endpoints without any reverse connections or alternative pathways. This is a unidirectional configuration for delivering electricity efficiently in simpler network setups;

– Fig. 2. Backward method illustration. Reverse gear: this configuration introduces a reversed pathway or alternative routing of power. It may represent fault-tolerant designs, where the network can reconfigure itself to ensure supply continuity in case of disruptions in the straight running configuration.

The Newton-Raphson method is widely used in power system analysis due to its high convergence rate and quadratic convergence property, meaning that the error decreases exponentially with each iteration. This makes it particularly effective when the initial approximation is close to the true root.

However, the method's efficiency decreases when the initial guess is inaccurate, or when the function's derivative near the root is close to zero, potentially leading to divergence or slow convergence.

In the electric power industry, the Newton-Raphson method is extensively applied for power flow analysis and system stability assessments. Its ability to efficiently solve nonlinear equations makes it an indispensable tool for modeling smart grids and networks with distributed generation [16]:

$$f(x)=0. \tag{7}$$

The Newton-Raphson method, or tangent method, is a numerical approach for finding the roots of nonlinear equations. Its principle is that each subsequent approximation $xk+1$ is calculated as the point of intersection of the tangent drawn to the graph of the function $f(x)$ at the current point $(xk, f(xk))$ with the abscissa axis OX. The idea behind the method is to replace the nonlinear function by a linear approximation on a small interval, thus quickly reducing the difference between the current approximation and the exact solution of the equation. This approach is not only intuitive, but also extremely effective in finding roots of complex nonlinear equations.

In conditions of complex power calculations, for example, when modelling distribution networks, the Newton-Raphson method can be used for flow distribution and stability analysis. Its use is justified when accuracy is crucial, for example, when optimizing relay protection parameters or setting up automatic network control.

The above methods demonstrate high efficiency in calculations of electric modes in distribution networks operating on the basis of the static principle. In such networks, the configuration remains unchanged over long periods of time and the main power source is a centralized energy hub.

Among the existing approaches, the Newton-Raphson method stands out for its versatility and ability to deal with nonlinear dependencies. Its high accuracy and fast convergence make it most suitable for modelling networks with variable parameters and complex structure. The use of this method allows taking into account dynamic changes in power flows and adapting calculations to changing network topology, which is especially important for modern smart grids. In addition, the method provides a stable solution to problems related to forecasting and optimization of network parameters, even in conditions of high variability of load and generation.

5. Results of reliability assessment of distribution grids up to 110 kV

5. 1. Factors affecting reliability

Markov processes allowed the temporal dynamics of failure and recovery to be modelled, which provided a high reliability of system failure estimation. Estimating the probability of node and branch states made it possible to identify the most vulnerable elements of the network and prioritize preventive measures.

The Newton-Raphson method is preferred for problems with nonlinear equations where high accuracy and convergence speed are required. Markov processes are better suited for analyzing reliability in the long term, taking into account dynamic changes in the system. The combined use of both approaches allows for a more comprehensive assessment of distribution networks Table 1.

Table 1

Comparison of Newton-Raphson method and Markov processes in network analysis

Criterion	Newton-Raphson method	Markov processes
Main objective	Solving nonlinear equations such as power flow distributions in a network	Modelling systems with respect to their dynamic behavior over time
Applicability	Complex networks with nonlinear dependence between nodes and elements	Reliability of distribution networks considering failure and recovery
Data type	The analytic form of a function and its derivative is required	State probabilities and failure times are used
Metrics	Fast convergence (quadratic)	Probability of states of the system
	Number of iterations until convergence	Average recovery time
	Estimation error in each iteration	Failure rate
Results	High accuracy when the initial approximation is close to the real solution	A complete analysis of the state of the system over a long period of time
	Stability under correctly chosen conditions of initial approximation	Ability to account for various factors affecting failure
Restrictions	Sensitivity to initial approximation	Dependence on the assumption of an exponential distribution of failures
	Errors are possible for derivatives close to zero	Difficulties in accounting for nonlinear processes and rapidly changing parameters
Advantages	Fast convergence (quadratic rate)	Ability to model complex network states with dynamics
	Suitable for networks with variable configuration	Easy integration of failures and recoveries
Examples of use	Calculation of power flows	Reliability of nodes and branches of distribution networks
	Optimization of relay protection parameters	Long-term reliability assessment of redundant systems

Equivalence principles are a fundamental approach to analyzing complex electrical networks, allowing to simplify their topology without losing key characteristics. The essence of equivalence is the replacement of complex network sections with equivalent models that preserve parameters critical for calculation and reliability assessment. This method is widely used in the analysis of power distribution networks to reduce computational complexity, especially in large power systems. The equivalence process involves the extraction of basic elements such as nodes and branches, replacing them with generalized parameters such as equivalent resistances, voltages or powers.

The application of equivalence principles is particularly relevant for modelling the operation of networks in emergency and post-repair modes, as well as for the integration of new elements such as distributed generation or intelligent control devices [17–19].

Matrix calculation of reliability indices is one of the effective methods of analysing the reliability of nodes of electric distribution networks (EDN).

Further, for each node the branches are equivalent, which makes it possible to assess the impact of failures of individual elements on the performance of the node as a whole. It is taken into account that in complex networks with parallel connections, the failure of one element does not always lead to the failure of the node, because the load can be redistributed to other branches. Fig. 3, 4 show the matrix calculation of reliability indicators.

$$
\begin{matrix}
0 & 0.0022 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.0022 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.676 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1.3 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.01 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.01 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1.3 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.832 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.01 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.01 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.832 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{matrix}
$$

Fig. 3. Failure frequency matrix

$$
\begin{matrix}
0 & 41 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
41 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 16.7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 16.7 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 11 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 11 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1.3 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 16.7 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 11 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 11 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 16.7 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{matrix}
$$

Fig. 4. Matrix of recovery time

This matrix serves as a key tool for a comprehensive assessment of the reliability of the entire system. It reflects how much each component and node in the network is capable of maintaining continuous operation, which is particularly important for making informed decisions in network planning and operation. The data from the availability matrix provides an accurate assessment of which elements of the system require more attention and helps to optimize maintenance schedules to minimize the risk of failure. The availability matrix method not only simplifies reliability analyses of complex network structures, but also provides a basis for developing strategies to improve system resilience. This approach ensures accuracy and reliability in predicting network behavior.

5. 2. Development of computational techniques to ensure applicability to various network configurations

The Table 2 allows to identify the most vulnerable elements of the distribution network, plan preventive measures and assess the impact of failures on the overall reliability of the system.

Table 2

Reliability indices of the equivalent branches

$i–j$	$w_{i–j}$, times/year	$T_{i–j}$, h/year	$t_{i–j}$, h	PS equipment
1–2	0.893	3.935	4.37	Overhead line (overhead line 1), length 60 km
1–2	0.893	3.935	4.37	Overhead line (overhead line 2), length 60 km
1–4	1.152	5.046	4.38	Overhead line (overhead line 3), length 80 km
4–5	0.005	0.2	40	Switch
5–4	0.005	0.2	40	Switch
5–9	0.575	2.499	4.36	Overhead line (overhead line 4), length 35 km
9–5	0.575	2.499	4.36	Overhead line (overhead line 4), length 35 km
9–10	0.0049	0.22	39	Switch
10–9	0.0049	0.22	39	Switch
10–11	0.0049	0.22	39	Switch
11–10	0.0049	0.22	39	Switch
2–10	0.0049	0.22	39	Switch
3–11	0.0049	0.22	39	Switch
4–6	0.019	0.719	41	Transformer (6.3 MBA)
5–7	0.019	0.719	41	Transformer (6.3 MBA)
6–8	0	0	0	Logical branch
7–8	0	0	0	Logical branch
11–12	0.0049	0.22	39	Switch
10–13	0.0049	0.22	39	Switch
12–14	0.142	0.617	4.39	Overhead line (OL 6), length 12 km
18–20	0.142	0.617	4.39	Overhead line (OL 6), length 12 km
19–21	0	0	0	Logical branch
22–21	0.011	0.12	10	Disconnector
21–23	0.015	0.99	72	Transformer (10 MBA)
20–22	0	0	0	Logical branch
21–22	0.011	0.12	10	Disconnector
22–24	0.015	0.99	72	Transformer (10 MBA)
23–25	0	0	0	Logical branch
24–25	0	0	0	Logical branch
20–26	0.5	2.188	4.39	Overhead line (OL 7), length 40 km
19–27	0.5	2.188	4.39	Overhead line (OL 7), length 40 km
26–27	0.011	0.12	10	Disconnector
27–28	0.019	0.74	41	Transformer (2.5 MBA)

For overhead lines (overhead lines) it is accepted to use a single-circuit design, with an average failure rate of =1.29 failures per 100 km per year. The recovery time and failure rate of network branches are calculated based on the data presented in [20].

The results of the analysis, summarized in Table 3, make it possible to identify the key reliability features of the distribution network nodes. In particular, the busbars of substation PS 1, represented by logic nodes 10 and 11, show marked differences in reliability levels in terms of ensuring uninterrupted power supply.

Table 3

Equivalent reliability indices of DEN nodes

Node	w_j	t_{Bj}	T_j
2	0.8939	4.379	3.92447
3	0.8939	4.379	3.92447
4	0.0008	2.336	0.00169
5	0.0007	2.617	0.00168
6	0.0186	38.547	0.73269
7	0.0185	38.747	0.72165
8	3.07E-06	19.326	0.00007
9	4.489E-05	3.996	0.000174
10	8.61E-07	2.159	0.000001
11	2.42E-05	3.983	0.00010
12	0.0049	39.829	0.20011
13	0.0049	39.994	0.20100
14	0.0187	62.036	1.18023
15	0.0187	62.103	1.20000
16	5.13E-06	31.036	0.00016
17	0.0049	39.829	0.20100
18	0.0049	39.994	0.20009
19	0.1459	5.603	0.81681
20	0.1459	5.604	0.81673
21	3.01E-05	2.886	0.00008
22	3.01E-05	2.886	0.00008
23	0.0139	69.858	0.98007
24	0.0139	69.858	0.98007
25	3.141E-06	34.929	0.00012
26	0.6449	4.657	3.00310
27	0.0005	2.353	0.00105
28	0.0186	39.078	0.72106

Analysis of the data in Table 1 allows to conclude that there are differences in the reliability of substation busbars of substation 1, represented by nodes No. 10 and No. 11, from the point of view of ensuring continuous power supply. It is found that these differences are due to the number of connected branches: node No. 10 has two incoming branches, which increases its structural reliability, while node No. 11 is connected by only one branch, which limits its functionality. In addition, the series connection of the busbars via a switch has an additional impact on the overall system reliability, creating potential points of failure. The presented data emphasize the need to take into account the topological features of the network and the interconnections between the elements when carrying out reliability analysis of distribution networks.

The analysis of the obtained data convincingly demonstrates that node No. 8 has the highest level of reliability among all load nodes, which is directly caused by the topological characteristics of the network. The substation SS 2, to which this node belongs, operates with two-way supply, providing a high level of redundancy and fault tolerance. In contrast, node 28 shows minimal reliability performance. This is due to the single-transformer configuration of substation SS 4, which significantly limits its redundancy and makes it more vulnerable to emergencies.

6. Discussion of the research results and implications for reliability improvement

In modelling distribution networks, the Newton-Raphson method demonstrated quadratic convergence and high accuracy in calculating power flows. Accurate results were achieved for networks with variable configuration, but the method required a qualitative initial approximation.

As shown in Table 1, the Newton-Raphson method is highly effective for solving nonlinear equations related to power flow calculations due to its fast quadratic convergence and suitability for networks with variable configurations. However, its accuracy strongly depends on a well-chosen initial approximation, making it less reliable when initial values are poorly estimated. In contrast, Markov processes excel in long-term reliability analysis, as they account for system failures and recovery rates over time. They provide a probabilistic framework to assess node and branch reliability, making them particularly useful for identifying weak points in the network and prioritizing maintenance.

Moreover, the combined methodology is particularly valuable for modern smart grids. The Newton-Raphson method can optimize power flow in real-time, considering factors like distributed energy resources, while Markov processes can evaluate the reliability and resilience of the system under various failure scenarios. This integration allows utilities to predict and mitigate risks, ensuring stable operation and reducing the likelihood of cascading failures.

Additionally, these methods complement each other in scenarios involving changing network topologies or the integration of renewable energy sources. The Newton-Raphson method can quickly adjust to shifts in configuration, while Markov processes can evaluate the impact of these changes on overall system reliability. Together, they provide a holistic view that enhances both short-term operational efficiency and long-term network stability.

In summary, while the Newton-Raphson method and Markov processes excel in their respective domains, their combined application enables a more comprehensive and effective strategy for modelling and managing distribution networks.

The study demonstrates that nodes with high redundancy levels (e.g., Node 8) exhibit exceptional reliability, exceeding 99.99 %, as shown in Table 3. This outcome underscores the role of network topology and redundancy in enhancing system stability. Conversely, nodes with single-transformer configurations (e.g., Node 28) show significantly lower reliability, with extended recovery times of up to 40 hours. The Markov process model captured these dynamics effectively, as shown by the accurate estimation of failure probabilities and recovery times.

Fig. 3, 4 illustrate the application of equivalence principles, enabling the simplification of network topologies for reliability calculations. This approach improved the accessibility and accuracy of the analysis. Furthermore, (1) provided insights into the temporal dynamics of failures and recoveries, identifying nodes with the highest likelihood of failure. These findings align with the goals outlined in Section 3, validating the methodology.

The proposed approach combines the Newton-Raphson method and Markov processes, leveraging their respective strengths for different aspects of reliability assessment. Unlike traditional static methods, which often fail to account for dynamic system changes, the Markov process model dynamically captures the temporal evolution of failures and recoveries. This advantage was highlighted by the comparison in Table 1, where Markov processes proved superior for long-term reliability assessment.

In contrast to alternative methods (e.g., predictive machine learning models in [21, 22]), the proposed approach integrates failure dynamics with recovery estimations. For instance, while machine learning predicts failures accurately, it lacks recovery time modeling. The integration of equivalence principles further distinguishes the methodology by simplifying complex topologies without compromising accuracy.

The results confirm that the proposed solutions significantly mitigate the high failure rate of overhead lines, prolonged recovery time of critical nodes, and the vulnerability of single-transformer configurations. Nodes with added redundancy (e.g., Node 8) demonstrated resilience to failures, directly addressing the vulnerabilities of single-transformer configurations. Moreover, the methodology's adaptability to various topologies ensures its applicability across diverse distribution networks, thereby filling the research gap identified earlier.

The study assumes a constant failure rate, modelled as an exponential distribution, which may not fully capture the effects of equipment aging and variable operating conditions. Additionally, the methodology was tested on networks up to 110 kV; its application to higher voltage grids or those with a high share of RES requires further validation and adaptation.

Despite its advantages, the model does not account for non-linear phenomena such as sudden load changes or extreme weather conditions. This limitation may affect its applicability in highly dynamic environments. Furthermore, the Newton-Raphson method's sensitivity to initial parameters can lead to errors if the starting values are poorly chosen.

To enhance the methodology, future work should focus on:

– developing hybrid models that integrate Markov processes with machine learning techniques for improved failure prediction and recovery time modeling;

– extending the methodology to include non-linear failure dynamics and incorporating real-time data from Smart Grid systems;

– adapting the approach for trunk grids and high-voltage networks, considering their increased complexity and dynamic nature.

These advancements will broaden the applicability of the proposed solutions, enabling real-time adjustments and increased resilience of modern distribution networks.

The analysis of distribution electric networks has shown the need to study the relationship between structural and functional reliability, as well as to develop recommendations for improving efficiency using modern technologies. The main causes of outages are related to equipment wear, insufficient maintenance and complex operating modes.

Existing methods for calculating network parameters do not take into account their dynamic configuration, which requires new approaches. For radial networks, the forward/reverse method is suitable, and for ring networks, Newton's methods, such as Newton-Raphson, are suitable. An integrated approach allows for an accurate assessment of the network condition and increases its reliability, which helps improve the efficiency of the distribution system DEN.

7. Conclusions

1. Major failure factors include equipment wear and tear (34.9 % of failures), climatic effects (24.7 %) and insufficient redundancy. Nodes with low levels of redundancy (No. 28) were found to have minimal reliability performance. Equipment recovery time in vulnerable nodes is up to 40 hours, which is significantly higher than the recovery time in highly redundant nodes. The failure rate of nodes such as 1–2 is 0.893 failures per year and the average recovery time is 4.37 hours, which confirms the effectiveness of the proposed approach.

2. The methodology is successfully adapted to networks with different topologies. Nodes with two-way redundancy (No. 8) have demonstrated high resilience to failures. The reliability of nodes with two-way redundancy exceeds 99.99 %, which confirms the importance of adding redundant links at vulnerable locations.

Conflict of interest

The authors declare no conflict of interest.

Financing

The study has carried out without financial support.

Data availability

Data will be available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

References

1. Singh, S., Singh, S. (2024). Advancements and Challenges in Integrating Renewable Energy Sources Into Distribution Grid Systems: A Comprehensive Review. Journal of Energy Resources Technology, 146 (9). https://doi.org/10.1115/1.4065503
2. Kaverin, V., Abisheva, D., Em, G., Kalinin, A., Yugay, V. (2022). Studying Partial Discharge Currents of High Voltage Power Line Suspension Insulators. International Journal on Energy Conversion (IRECON), 10 (3), 88. https://doi.org/10.15866/irecon.v10i3.21769
3. Kayumov, D., Bulatbaev, F., Kayumova, I., Breido, J., Bulatbayeva, Y. (2023). An engineering approach for the qualitative assessment of the luminous flux of led lamps. International Journal of Energy for a Clean Environment, 24 (1), 31–43. https://doi.org/10.1615/interjenercleanenv.2022043776

4. Wang, Y., Zheng, Q., Guo, M., Xiao, H., Si, C., Chen, W. (2022). Reliability Improvement of Distribution Network with Distributed Generation Sources and Diversified Loads. LOW VOLTAGE APPARATUS, 2, 63–67. Available at: http://www.eaes-seari.com/Jwk_dqynxgljs/EN/abstract/abstract480.shtml
5. Soltan, S., Mazauric, D., Zussman, G. (2017). Analysis of Failures in Power Grids. IEEE Transactions on Control of Network Systems, 4 (2), 288–300. https://doi.org/10.1109/tcns.2015.2498464
6. Wu, Y., Fan, T., Huang, T. (2020). Electric Power Distribution System Reliability Evaluation Considering the Impact of Weather on Component Failure and Pre-Arranged Maintenance. IEEE Access, 8, 87800–87809. https://doi.org/10.1109/access.2020.2993087
7. Tatkeyeva, G., Bauyrzhanuly, M., Gaukhar, A., Assainov, G., Khabdullina, G., Tangirbergen, A. et al. (2024). Development of the logical system for forecasting wind characteristics in the urban conditions. EUREKA: Physics and Engineering, 2, 55–69. https://doi.org/10.21303/2461-4262.2024.003305
8. Li, S., She, Y., Shi, K., Chen, Z. (2022). A Method for Evaluating Reliability and Failure Rate of DC Circuit Breakers. 2022 Global Conference on Robotics, Artificial Intelligence and Information Technology (GCRAIT), 578–581. https://doi.org/10.1109/gcrait55928.2022.00126
9. Cao, H., Song, Y., Wang, S., Dai, F., Liu, J., Cheng, Q. (2024). Failure Mode Analysis and Identification Method Based on the External Characteristics of DC Circuit Breaker. 2024 China International Conference on Electricity Distribution (CICED), 01–05. https://doi.org/10.1109/ciced63421.2024.10754216
10. Pande, P., Hussain, K., Pravallika, B., Al Ansari, M. S., Tharsanee, R. M., Acharya, S. (2024). Predictive Maintenance of Power Transformers in Distribution Network with Energy Management Using Deep Learning. 2024 5th International Conference on Intelligent Communication Technologies and Virtual Mobile Networks (ICICV), 581–586. https://doi.org/10.1109/icicv62344.2024.00098
11. Biradar, V., Kakeri, D., Agasti, A. (2024). Machine Learning based Predictive Maintenance in Distribution Transformers. 2024 8th International Conference on Computing, Communication, Control and Automation (ICCUBEA), 1–5. https://doi.org/10.1109/iccubea61740.2024.10774993
12. Reddy Shabad, P. K., Alrashide, A., Mohammed, O. (2021). Anomaly Detection in Smart Grids using Machine Learning. IECON 2021 – 47th Annual Conference of the IEEE Industrial Electronics Society, 1–8. https://doi.org/10.1109/iecon48115.2021.9589851
13. Papaspiliotopoulos, V. A., Korres, G. N., Hatziargyriou, N. D. (2015). Protection coordination in modern distribution grids integrating optimization techniques with adaptive relay setting. 2015 IEEE Eindhoven PowerTech, 1–6. https://doi.org/10.1109/ptc.2015.7232558
14. Rêma, G. S., Bonatto, B. D., de Lima, A. C. S., de Carvalho, A. T. (2024). Emerging Trends in Power Transformer Maintenance and Diagnostics: A Scoping Review of Asset Management Methodologies, Condition Assessment Techniques, and Oil Analysis. IEEE Access, 12, 111451–111467. https://doi.org/10.1109/access.2024.3441523
15. Carletti, E., Amadei, F., Franzone, G., Rizzati, J., Cocchi, L., Bolognesi, M., Moschella, P. (2023). The reliability of the electrical distribution system using the Markov Modeling methodology. IET Conference Proceedings, 2023 (6), 1115–1119. https://doi.org/10.1049/icp.2023.0655
16. Borges, C. L. T., Cantarino, E. (2011). Microgrids Reliability Evaluation with Renewable Distributed Generation and Storage Systems. IFAC Proceedings Volumes, 44 (1), 11695–11700. https://doi.org/10.3182/20110828-6-it-1002.01090
17. Song, H., Zhang, B., Wang, M., Xiao, Y., Zhang, L., Zhong, H. (2022). A Fast Phase Optimization Approach of Distributed Scatterer for Multitemporal SAR Data Based on Gauss–Seidel Method. IEEE Geoscience and Remote Sensing Letters, 19, 1–5. https://doi.org/10.1109/lgrs.2021.3077493
18. Hu, W. J. (2021). Momentum Method for Improving the Convergence of Newton-Raphson Method for Nonlinear Circuit Transient Simulations. 2021 IEEE International Conference on Computer Science, Artificial Intelligence and Electronic Engineering (CSAIEE), 296–303. https://doi.org/10.1109/csaiee54046.2021.9543125
19. Wei, J., Cai, H., Jiang, T., Westermann, D. (2021). Research on Power System Network Equivalent with Different Methods. PESS 2021; Power and Energy Student Summit.
20. Gupta, A. P., Mohapatra, A., Singh, S. N. (2018). Power System Network Equivalents: Key Issues and Challenges. TENCON 2018 – 2018 IEEE Region 10 Conference, 2291–2296. https://doi.org/10.1109/tencon.2018.8650397
21. Aghili, J., Franck, E., Hild, R., Michel-Dansac, V., Vigon, V. (2025). Accelerating the convergence of Newton's method for nonlinear elliptic PDEs using Fourier neural operators. Communications in Nonlinear Science and Numerical Simulation, 140, 108434. https://doi.org/10.1016/j.cnsns.2024.108434
22. Ramli, S. P., Usama, M., Mokhlis, H., Wong, W. R., Hussain, M. H., Muhammad, M. A., Mansor, N. N. (2021). Optimal directional overcurrent relay coordination based on computational intelligence technique: a review. Turkish Journal of Electrical Engineering and Computer Sciences, 29 (3), 1284–1307. https://doi.org/10.3906/elk-2012-98