

KAUNAS UNIVERSITY OF TECHNOLOGY
LITHUANIAN ENERGY INSTITUTE

GINTVILĖ ŠIMKONIENĖ

**EVALUATING THE APPLICABILITY OF RELIABILITY MODELS
FOR THE ELECTRIC DISTRIBUTION NETWORK**

Summary of Doctoral Dissertation
Technological Sciences, Energetics and Power Engineering (T 006)

2023, Kaunas

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PRITAIKOMUMO TYRIMAS**

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INTRODUCTION

Relevance of the work

There are 2,400 electric distribution network companies in the EU, with 260 million consumers connected to electric distribution networks, 99 % of whom are households and small businesses. Lithuania's electric distribution networks (EDNs) are more than 126,600 km long, with the largest part of the network (98,5 %) located in suburbs and small towns. The network is dominated by 94 % 10 kV overhead lines.

Today, most of the 0,4–35 kV electric distribution network and its components operating in Lithuania have a service life of more than 30 years. Faults, lack of grid capacity and transmission capability, long repair and restoration times, and high energy losses complicate the operation of the electricity system. The distribution network system has a passive characteristic, and persistent faults affecting the quality of electric energy transmission along with the values of the reliability indicators do not ensure the quality of electric energy supply and do not meet the needs of consumers.

The recorded data on the electric network faults and outages since 2012 to assess the reliability of Lithuania's electric distribution networks are not accurate and reliable, and therefore the assessment and the results do not adequately reflect the real situation of the EDN. The assessment of the network reliability is abstract, and the methodology for solving the problem area is applied to the entire Lithuanian electric network. The current calculation methodology does not address the requirements of the weakest parts of the electric network system, the level of satisfaction of electric energy consumers, and the reliability levels of the network. The situation is further complicated by the assessment of the reliability of the EDN in EU countries. To date, there is no common understanding among EU countries on how to calculate the reliability of EDN by using uniform indicators with the same content and comparability. There are no common and specific measures to address the prevailing problems, no rules substantially and fundamentally for recording cancellations, no clearly defined norms, and no common and unified calculation methodology for quality standards. EU countries have different ways of identifying electric network outages and faults, and different methodologies for collecting data on network faults and outages. In this context, different technical parameters of the network complicate the reliability assessment. Countries apply their own available and established indexes for assessing the reliability of the EDN while taking into account the technical parameters, along with the outage and restoration times as regulated in the specific country under discussion.

In order to improve the reliability of the EDN and the uninterrupted supply of electric energy, there is a need for continuous monitoring and analysis of the electric network, identification of the most sensitive areas of the network, the frequency and intensity of faults, the amount of undelivered electric energy to consumers, and the choice of the appropriate technological solutions and methodologies for assessing reliability.

Aim of the work

The aim of the present thesis is to develop a methodology for the assessment of the electric distribution network so that to assess the most sensitive areas of the network and the need for network upgrades in order to improve reliability performance in the face of uncertain electric network fault data.

Objectives of the work:

1. To develop a methodology for the assessment of the reliability of the electric distribution network, which includes the selection of criteria for assessing reliability, calculation algorithms that allow to assess the influence of different factors on the reliability indexes and to select the optimal solutions to increase the reliability of the electric supply;
2. Develop an algorithm for the assessment of the reliability of the electric network using the Max-Flow method for the assessment of the reliability of the electric energy supply;
3. To develop an algorithm for assessing the desirability of upgrading the electric network, thus allowing the evaluation of different factors in the decision to retrofit the electric network;
4. To apply the developed reliability assessment methodology to make the optimal decisions on the advisability of upgrading the electric distribution network to improve reliability.

Research novelty. The developed methodology for assessing the reliability of the electric distribution network, based on Monte Carlo and Max-Flow algorithms, extends the capability of assessing the reliability of the electric energy supply when the topology of the electric network is changed. The Game Theory approach allows to determine the most appropriate mutual strategy choice of the players in the context of electric energy failures. And the integrated application of the methods provides a more comprehensive and reliable assessment of electric network reliability indexes.

Practical value of the work. A methodology for assessing the reliability of the electric distribution network has been developed to assess the reliability and capacity and availability of electric energy to consumers. These calculation methodologies can be used to predict grid failures, analyse different grid configurations and make more efficient grid planning decisions, thereby resulting in an improved grid reliability and uninterrupted electric energy supply to consumers. This can be useful for the grid operators to react more quickly to emergency situations, to properly plan grid configurations, and to make strategic decisions, while ensuring a reliable supply of electric energy to consumers as well as reducing the cost of electric energy supply.

Thesis defence statements:

1. The methodology developed for the assessment of the reliability of the electric distribution network allows assessing, from the technical and economic points of view, the changes in the reliability of the electric energy supply following the implementation of different solutions.
2. The Max Flow method can be used to assess the reliability of the electric energy supply.
3. Game Theory can be used to justify decisions to modify the electric network to improve the reliability of electric energy supply.
4. The developed methodology for the reliability assessment allows selecting the optimal solutions for the modernisation of the electric distribution network, while taking into account the technical and economic impact of the solutions on the reliability of electric energy supply.

Methods applied in the research. methods used in the doctoral thesis were chosen according to the objectives of the study and the amount of available data. The methods used in the thesis are as follows:

1. Systematic analysis of the relevant literature and documents to support the theoretical framework: a detailed comparative analysis of scientific literature and documents was carried out to analyse the meaning of the concept of reliability, the indexes used to assess reliability, and the methods in use.
2. Calculation methods: *MATLAB* and *Python* simulation programs were used for the calculations. They allowed for reliability assessment calculations and simulations.
3. Data organisation, grouping, systematisation, analysis and processing by using the *Microsoft Office* software package, *MATLAB Plotting* library, graphical evaluation methods.

Scientific publicity. The results of the research on the topic of the dissertation have been presented at 7 international conferences (of which, 3 international conferences organised abroad), whereas the most important results of the research have been published in 5 scientific articles in peer-reviewed periodical journals published in international databases.

Structure and scope of the dissertation. The doctoral dissertation consists of: introduction, literature review, research methodology, research results, discussion sections and conclusions, a list of references, curriculum vitae, a list of articles and conferences, acknowledgements and annexes. The main body of the dissertation is presented in 127 pages. The main part of the dissertation contains 67 figures, 32 tables and 155 references, and is supplemented with 9 annexes.

1. RELIABILITY ASSESSMENT OF ELECTRIC ENERGY SYSTEMS

1.1. The Concept of Reliability and its Implications for Electric Energy Supply

Reliability is an indexes of the quality of an asset which shows its level of functionality and its ability to maintain the specified performance tolerances, while taking into account maintenance, repair and other external and internal conditions affecting the network (see Fig. 1.).



Fig. 1 Reliability components

In the context of the electric network, the meaning of reliability is influenced by a few factors (both *external* and *internal*) determining the values of the indexes and the assessment of reliability itself. In this case, reliability can also be defined as a generic characteristic: the complex set of characteristics of outages, faults, recoveries (see Fig. 2) (Gono *et al.*, 2007; Navickas, 2007; Gono *et al.*, 2011; Gečys, 2011; Višniakas, 2015; Liu, 2019).

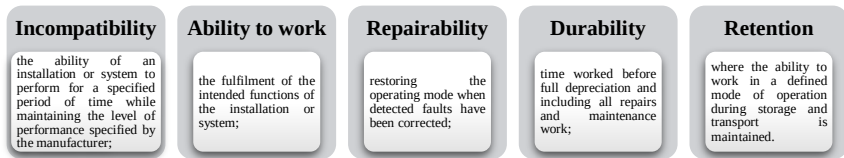


Fig. 2 Reliability assessment under site and operating conditions

Reliability is defined as a characteristic and a key criterion describing the performance and stability of the power system, the ability of the grid to be operational and to supply electric energy in different operating modes.

1.2. Analysis of Power Outages and Faults

A power system malfunction, interruption of the power grid and power supply can be defined as a **failure** or **fault** which partially or totally incapacitates an asset and affects the reliability of the power system (Chen *et al.*, 2019; Furse, 2021). Power cuts can be *planned* or *unplanned*. Scheduled repairs are carried out according to the plan and/or according to the fault that has occurred. An unplanned outage is defined as an accidental failure of the electric network that occurs without a prior warning to the consumer (EN 50160, Economy of the Republic of Lithuania; 2005, No. 4-265). Unplanned power outages are divided

into short-term, *permanent* (<3 minutes) and *long-term*, (12–24 hours) and ‘*catastrophic*’ (more than 24 hours) (Kornatka, 2017).

The frequency of faults and outages depends on the location of the country, the structure of the energy system, the number and specificity of the installations, and the reliability of their operation. Electric network faults and power outages can complicate the operation of the power system and cause significant economic losses (Liu *et al.*, 2020). An individual outage is an episodic event from which the quality of supply cannot be assessed and therefore cannot reflect the reliability of the whole system.

1.3. Analysis of Reliability Indexes for the Electric Distribution Network

In power grid reliability calculations, two types of reliability indexes are distinguished: *basic* and *additional*. Using only the basic reliability indexes would make it difficult to assess the current technical state of the network, as the individual index calculations do not describe the functioning and the status of the network. Also, the results do not always provide an assessment of the functioning of the electric network and its appropriate response to equipment or network faults as well as outages.

The most commonly used indicators by EU countries are SAIDI (*System Average Interruption Duration Index*), SAIFI (*System Average Interruption Frequency Index*), MAIFI (*Momentary Average Interruption Frequency Index*), CAIDI (*Customer Average Interruption Duration Index*), ENS (*Energy not Supplied*); AIT (*Average Interruption Time*) additional reliability indexes (Sekhar *et al.*, 2016; Zuliani *et al.*, 2017). Their use is regulated and approved on a country-by-country basis, depending on the technical characteristics of the networks. The dependence of the reliability of a load node on the reliability level of the whole power system is very significant, and it is an integral element of the system functioning. A mapping of the identity of the indexes at the load node and system levels is given in Table 1 below.

Table 1 Reliability calculation indexes for load node and system levels

Reliability index for the load node	Reliability index at system level and for the load node
λ_{si} (number of failures/year)	SAIFI (number of interruptions per consumer/year)
r_{si} (number of hours/days)	SAIDI (duration of outages [min.] per consumer/year)
U_{si} (hours/year)	CAIDI (hours/faults)
LOE_{si} (kWh/year)	AENS (kWh per consumers/year)

There is no common agreement in the EU countries on how to calculate reliability, on the basis of default and set indexes, and on the methodology for calculating it. Reliability indexes must be chosen in such a way that they provide

a comprehensive, comparable and meaningful picture of the state and evolution of reliability.

1.4. Author's Contribution to the Topic

An evaluation analysis of the choice of methods has been carried out while taking into account computational feasibility, data availability, accuracy and time resources. A methodology for the assessment of the reliability of the electric distribution network has been developed with the selection of reliability criteria (network load, average fault intensity, restoration time) and calculation algorithms based on the Monte Carlo and Max Flow methods. The methods in use are complementary, and they do not require a large amount of technical network data. They provide a comprehensive assessment of the reliability of the EVS and identify the arising problems. The software algorithm has been implemented in *MATLAB* and *Python frameworks*. The algorithm and the applied methods allow for a comprehensive assessment of the network status, reliability and the optimal decisions on the development of the network infrastructure and the reliability of the electric energy supply, which other methods fail to ensure.

The Max Flow approach can provide a detailed analysis of the reliability of the electric network when minimum technical parameters are available on the topology of the network, data on the line capacities, and the capacity of the consumers. Compared to physical models of electric networks used to solve flow distribution problems, it does not require detailed datasets covering the electric energy parameters (impedances, inductances, etc.) of power lines or transformers. The Max Flow method idealises the power grid, thereby allowing the estimation of power losses and grid voltage levels. It indicates whether the available topology of the electric network and the capacities of the network elements are sufficient to supply electric energy to consumers and indicates which consumers would be restricted or completely cut off from the electric energy supply in each network state.

The analysis uses a Game Theory calculation methodology which has been improved and applied in the reliability assessment of the Lithuanian electric distribution network. The Game Theory methodology allows for the assessment of strategic actions and interactions between participants, while taking into account their different goals and interests. The methodology allows for a detailed analysis of the different grid schemes, their reliability and their impact on the electric energy consumer and the Distribution System Operators (DSO). By identifying strategic actions and analysing the potential impacts, the approach allows for the selection of the most efficient solution for the benefit of electric energy consumers and DSOs.

The work has a practical benefit regarding the assessment of the need for design and modernisation of the electric network in order to ensure the reliability of the electric network.

2. ASSESSMENTS OF THE CURRENT STATE OF THE ELECTRIC DISTRIBUTION NETWORK'S RELIABILITY AND THE METHODS APPLIED

2.1. Designing the Research Methodology

The reliability assessment of the electric distribution network is influenced by data and statistics from the electric network. Proper data collection and assessment allows decisions to be taken to improve the reliability and stability of the electric network to provide uninterrupted electric to consumers.

The analysis of the Lithuanian electric distribution network shows that the 10 kV network must be given special attention. In the event of faults on the main lines, the majority of network consumers are disconnected. It depends only on the severity of the faults and the ability of the DSO to deal with the faults quickly and efficiently. It is therefore very important to pay attention to the current state of the DSO and, if necessary, to take optimal and cost-effective solutions. A flowchart of the research methodology was developed to assess the reliability of the EDN (see Fig. 3).

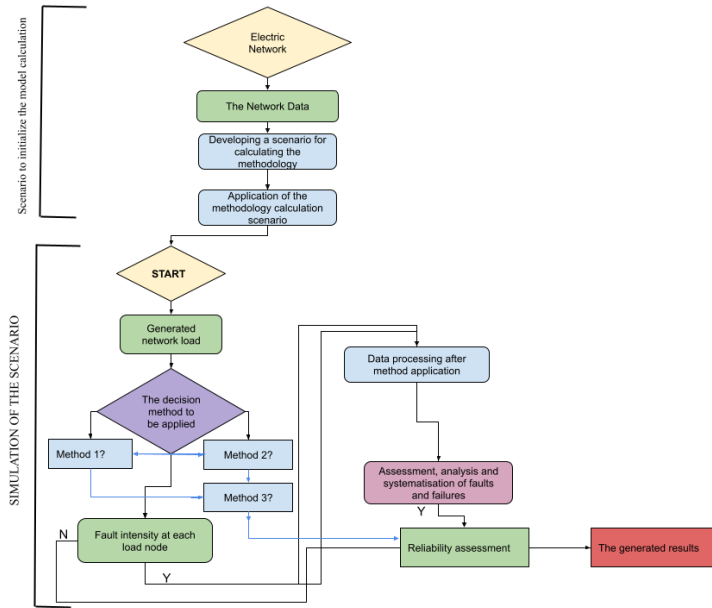


Fig. 3 Reliability Assessment Methodology Scenario

2.2. Reliability Assessment of the Electric Distribution Network

An algorithm has been developed to calculate the reliability of the EDN's (see Fig. 4) by using the Max Flow method to assess the reliability of the electric supply. The developed algorithm allows the assessment of the reliability of the network when changing the topology of the EDN, or when upgrading the network, replacing network equipment, and when different network states are prevailing. Reliability assessment is carried out by using a core set of extended indexes.

components), and the cumulative failure intensity is constant, i.e. unchanging. The methods in use produce statistical results and predictions which reflect the actual condition and reliability of the system. The calculation methodology is implemented in the *MATLAB* environment.

The distribution of faults in electric networks is a stochastic and constantly changing process depending on the above listed factors, the state of the network, and the external and internal conditions affecting it. In order to effectively manage the reliability of the electric network and to ensure a reliable supply of electric energy to consumers, taking into account cost-effectiveness, a game-theoretic approach is applied to select the optimal solutions. This approach allows the use of calculations and results to identify the optimal solution which would maximise the benefits for the players involved.

The simulations of the method are executed in the general-purpose programming language *Python* as a tool, and the principle of the game model is discrete events distributed over time. The simulations are run for a period of 50 years with errors of less than 1 %. The analysis is carried out on 3 grid schemes of different connection types, with a random distribution of fault frequency over time. The reliability assessment shows the robustness of a given network to withstand faults in order to minimise the number of outages. However, the calculation methodology and methods are subject to change, therefore requiring continuous improvement of the calculations while taking into account the network and the external influences acting on it.

2.3.1. Max Flow Method for Reliability Assessment

The method offers the advantage that relatively little initial data is needed to build a model of the power system: the network topology and the capacities of the network elements. The method can be used to calculate the optimal flow paths in the network by virtue of exploiting the potential of the electric network with the minimal impact on electric energy consumers. This helps to avoid over-consumption of electric energy and power losses, as well as improvement of the efficiency and reliability of the grid.

An electric system is described by a graph consisting of nodes and branches (see Fig. 5). The substations, generators and loads of the power system are modelled as nodes in the network (called *vertices* in the graph theory), while power lines and transformers are modelled as branches or edges of the graph. The electric network is represented as a graph $G = (V, E)$ with n vertices, distributed in a set of V and k edges E . The connection matrix $\mathbf{A}$ defines the topology of the graph. Interconnection matrix elements a_{ij} denote the weights of the side joining the two nodes. When $a_{ij} > 0$, this means that there is a connection between node i and node j . Available at $a_{ij} = 0$, there is no relationship between i and j .

The capacities of the power lines are chosen as edge weights. The flows are represented on the graph by a vector: $\varphi = (\varphi_1, \varphi_2, \varphi_3, \dots, \varphi_n) \in \mathcal{R}^P$. At each peak ($e_i \in E$), Kirchhoff's first law holds, i.e. the sum of the inflows into the peak would be equal to the sum of the outflows from the peak.

If the graph starts at s and ends at t , then the maximum expected flow from s to t will be the Max Flow of the graph, corresponding to the throughput of the network under consideration (Fang *et al.*, 2018). The *Ford-Fulkerson* algorithm is used to calculate the Max Flow. For an available graph $G = (V, E)$, with edge permeabilities $c = (u, v)$ and flows $f(u, v) = 0$, on all edges $u-v$, the maximum flow rate is determined (throughput) from source s to receiver t . At each step, the following conditions apply:

- $0 \leq f(u, v) \leq c(u, v)$;
- $f(u, v) = -f(v, u)$;
- $\sum_v f(u, v) = 0 \Leftrightarrow f_{in}(u) = f_{out}(u)$ – for all peaks, except for s and t .

A graph has been created $G_f = (V, E_f)$, whose capacity is calculated as:

$$c_f(u, v) = c(u, v) - f(u, v) + f(v, u) \quad (1)$$

For the purpose of the graph, the full capacities of generators and consumers are indicated:

$$S_{gen} = \sqrt{P_{gen}^2 + Q_{gen}^2} \quad (2)$$

$$S_{ap} = \sqrt{P_{ap}^2 + Q_{ap}^2} \quad (3)$$

here: P_{gen} ; Q_{gen} – Active and reactive power generated;

P_{ap} ; Q_{ap} – Active and reactive load power.

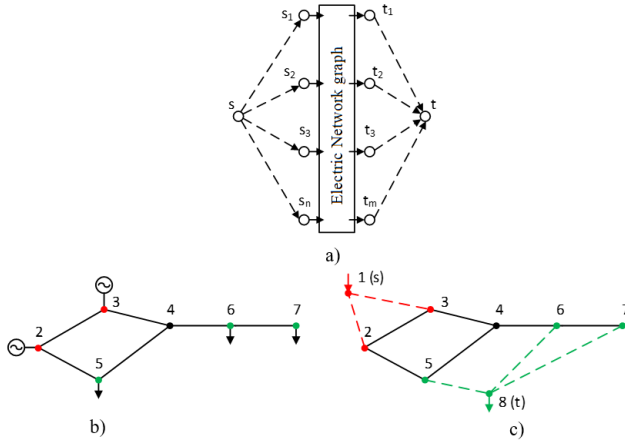


Fig. 5 Replacement of a graph with multiple sources and receivers by a graph with one virtual source and one virtual receiver (a), a diagram of the power grid (b) and its corresponding graph (c)

After the graph has been constructed, the states of the grid elements are generated by using the Monte Carlo method, and, for each grid state, the maximum flow is calculated by using the Max Flow method from the virtual source to the virtual receiver.

2.3.2. The Game Theory Approach for Reliability Assessment

Each game consists of moves, i.e., decisions and implementations by each player. Game strategies can be *random* and *personal*, where common rules are used and known to all players involved. In the energy sector, only personal strategies are suitable, as the common rules must prevail due to the prevailing exchanges and the players have to make the appropriate conscious choices.

The aim of the Game Theory is to recommend rational decision-making to the players, which would not only lead to rational decision-making strategies, but also, by including the electric network as a player's solution, to show the levels of reliability and the current state of the grid.

Based on a typical n player game (Cheng, Yu, 2018; 2019; 2020), which is referred to as a *Nesh* equilibrium, then, under the normal form of the game:

$$G = \langle N, S, U \rangle \quad (4)$$

The whole form of the game consists of three main elements:

1. Players' Set (Cuzanauskas, Anskaitis, 2015). The full set of players $N = \{1, 2, \dots, n\}$, and individual players are denoted: $i, j, k, \dots$ and so on.

here: N – a complete set;
 $n = |N|$ – the number of players in the set.

2. Strategies for each n players S_i (*configurations*) and strategic space $s_i \in S_i, i = 1, 2, \dots, N$:

$$S = \{S_1, S_2, \dots, S_n\} \quad (5)$$

here: S – denotes the strategic set of actors $i \in N$.

Strategic combination of all participants:

$$s = \{s_1, s_2, \dots, s_n\} \quad (6)$$

3. Each player's payback or utility function U_i , called $U_i(s)$ (Winning function – $f_i(x)$).

$$s_i \rightarrow R, i = 1, 2, \dots, N \quad (7)$$

$$u = \{u_1, u_2, \dots, u_n\} \quad (8)$$

The aim of players n is to reduce their payments and increase their income. If a player chooses S_i strategy, the other player or players will respond with strategy S_j . So, in the case of S_j , the strategy minimises S_i achievements.

Consumers pay a high price for electric energy, but they also need quality and fast restoration of the network in the event of an emergency. Therefore, an EDN system is needed to ensure not only the well-being of the DSO, but also the consumer's rights, due to the price to be paid for the service, to the increased allocation of appropriate investments for the maintenance and renewal of the network (see Fig. 6).

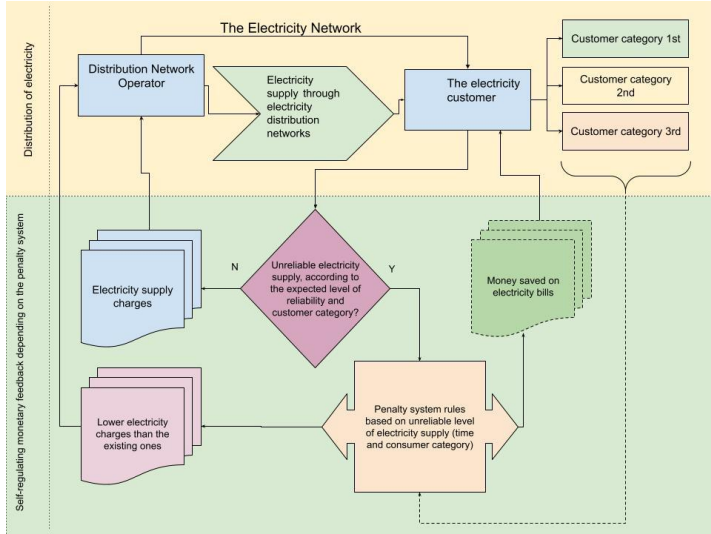


Fig. 6 Methodology for applying *Game Theory*

The Game theory analyses three different topologies of EDNs: a grid that is radial (see Fig. 7); a grid with independent feeders (see Fig. 8); and a grid that is radial, where there is more than one feeder (see Fig. 9). The expected disconnection time at node i when a fault recovery is performed can be calculated as follows:

$$A_i = \sum \lambda_i \cdot t_r \quad (9)$$

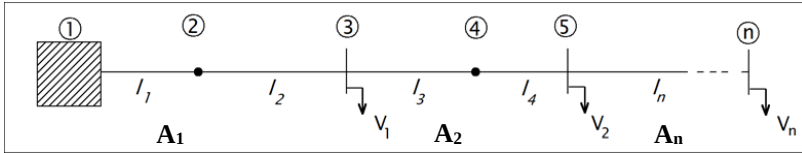


Fig. 7 Scheme 1 analysed by using a *Game Theory* computational methodology

The maintenance or failure of one element will result in the disconnection of the entire line, and all users of that line will lose their electric energy supply until the power supply has been restored to the working order. Where a fault has occurred in a node but there is no switch, then the condition may be written as:

$$A_1 = A_2 = A_n = (\lambda_1 + \lambda_2 + \lambda_n)t_r \quad (10)$$

The following condition is relevant and applicable to the 1st scheme analysed.

$$\sum_i t_i = A_1 + A_2 + A_3 = \lambda(t_r + 2t_s), t_t = 0 \quad (11)$$

here: A_1, A_2, A_n – load nodes.

The scheme shown in Fig. 8 has switches which disconnect parts of the network in the event of a network fault, as well as the possibility of switching the network and feeding power through another grid line.

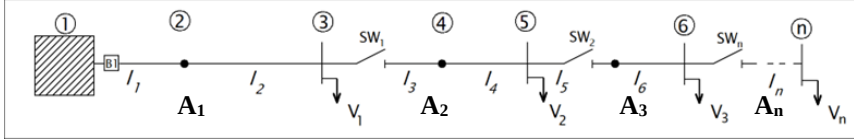


Fig. 8 Scheme 2 analysed by using *Game Theory* computational methodology

Network switches and additional power supplies can improve the network reliability and ensure faster restoration of the power supply to the consumers.

$$A_n = \left(\sum_{i=1}^N \lambda_n \right) t_r + (\lambda_n) t_s \quad (12)$$

The calculation methodology is presented for the different fault locations: $A_1; A_2; A_3$

$$\begin{cases} A_1 = (\lambda_1 + \lambda_2 + \lambda_3 + \dots + \lambda_n) t_r + (\lambda_2 + \lambda_3 + \dots + \lambda_n) t_s \\ A_2 = (\lambda_2 + \lambda_3 + \dots + \lambda_n) t_r + (\lambda_1 + \lambda_2 + \lambda_3 + \dots + \lambda_n) t_s \\ A_3 = (\lambda_3 + \dots + \lambda_n) t_r + (\lambda_1 + \lambda_2 + \lambda_3 + \dots + \lambda_n) t_s \end{cases}$$

This condition states: in the case of a fault in part A_1 , it is necessary to restore the faults in the first part of the circuit (l_1), and in the second part of the line (l_2), it is only necessary to connect the consumers to the grid; in case of a fault in both A_2 and A_1 , it is necessary to restore the faults in the first part of the circuit (l_1), to connect the consumers to the system, and to restore the faults in the second part of the line (l_2).

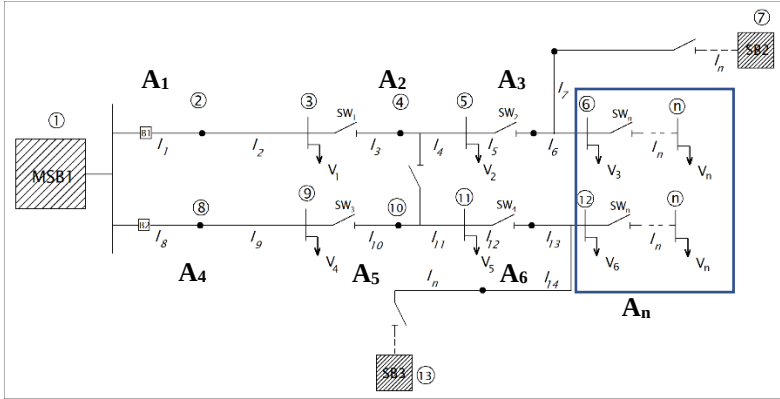


Fig. 9 3rd scheme analysed by using *Game Theory* computational methodology

Considering the different fault locations, a calculation methodology is presented for the analysis of Scheme 3 shown in Fig. 9:

$$\begin{cases} A_1 = \lambda_1 t_r + (\lambda_2 + \lambda_3) \cdot (t_s + t_t) \\ A_2 = \lambda_1 (t_s + t_t) + \lambda_2 (t_r + t_s) + \lambda_3 t_s \\ A_3 = (\lambda_1 + \lambda_2) (t_s + t_t) + \lambda_3 t_r \end{cases}$$

Thus, this calculation expression shows that each user chooses a level of reliability. It is known that the grid situation requires optimal decisions to be taken to ensure that the electric energy consumer is assured of an uninterrupted supply of electric energy.

2.3.3. Engineering Assessment of Measures to Upgrade the Electric Network

The cost of disconnections caused by faults in the electric distribution network shall be calculated according to the Formula:

$$C_j = \sum_{i \in I} \lambda_i \cdot \{a_j(t_{ij}) + b_j(t_{ij}) \cdot t_{ij}\} \cdot P_j \quad (13)$$

here: C_j – price of terminated power P_j and non-supplied electric energy at the node j ;

$a_j(t_{ij})$ – price per unit of unsupplied power (demand kW);

$b_j(t_{ij})$ – the unit price of unsupplied energy (demand kWh);

t_{ij} – disconnection time at a given node j for a given fault i .

Without assessing a specific rate, the cost of restoration can be described by a payback function:

$$C_{r_i} = t_r \cdot \lambda_{r_i} \quad (14)$$

here: λ_{r_i} – the frequency of the fault that is related to the restoration (recovery);

t_r – is the restoration time.

Switching costs are calculated as follows:

$$C_{s_i} = t_s \cdot \lambda_{s_i} \quad (15)$$

here: λ_{s_i} – the frequency of faults related to switching (power supply via another area or line of the network);

t_s – switching time.

The cost of interconnection (switching to another electricity line) is expressed as:

$$C_{tie_i} = t_{tie} \cdot \lambda_{tie_i} \quad (16)$$

here: λ_{tie_i} – the frequency of the fault occurring, which is related to the connection of the changeover to another supply line;

t_{tie} – switching the connection time.

The economic evaluation of the developed methodology assesses the effectiveness of changes in the reliability of the electric energy supply as a result of different solutions. The determined and selected optimal solution allows the evaluation of the rationale for the choices, which also has a clear link to the costs associated with the current state of the electric network and with the changes to the network topology, upgrades or replacements of electric equipment.

2.3. Summary of the Section

1. In Lithuania, the load on the electric distribution network is increasing annually (by about 8,5 %), and the demand for electric energy is also increasing (about 6 %). The majority of Lithuania's EDN's (98,5 %) are located in districts, small towns or rural areas. Overhead lines account for 94 % of the total 10 kV airline network. More than 80 % of all faults occur in EDN. The value of the SAIDI index has changed from 52,12 min/consumer to 201,95 min/consumer.
2. By using the Monte Carlo and MaxFlow methods, the network states are simulated for different operating conditions and available network data. The calculation methodology identifies the most sensitive areas of the network which require more maintenance and investment. The

methodology can help to avoid power bottlenecks and reduce the risks associated with faults. It can also reduce the amount of undelivered electric energy, reduce losses and increase the efficiency of the network to ensure the reliability of electric energy supply. The conclusions and results can help to reduce the probability of blackouts and improve the performance of the network.

3. The Game Theory approach can provide mutually beneficial rules and coordinated strategies that allow for mutual benefit. This cooperation helps to improve the reliability and supply of the grid, while optimising the welfare of electric energy consumers and DSOs. The Game Theory approach in the field of EDN renewal provides an opportunity to improve the reliability of electric energy supply, reduce losses and increase cooperation between consumers and DSOs. This leads to better results and more ambitious targets, thus ensuring mutual benefits and a better functioning of the electric network.

3. OPTIMISING TECHNICAL SOLUTIONS FOR THE RELIABILITY OF THE ELECTRIC DISTRIBUTION NETWORK

This section provides analysis of the change in the configuration of the electric distribution network, modernisation or changes to the electric energy installations. The assessment is carried out by evaluating the reliability of the network as a state. The analysis of the results and the application of the methods enable the evaluation of the optimisation of the technical solutions for the reliability of the grid, the selection of the most appropriate solution that provides the best conditions for those responsible for its distribution and supply, the State, and the electric energy consumers.

3.1. Benchmarking the Reliability of the Electric Distribution Network

The object of the analysis is the real 10 kV electric distribution network in the Lithuanian region (the names of power lines and substations are impersonal). A model of the electric network has been developed to study the reliability indexes of the power supply, with a total length of 214.2 km of power lines, of which, 172.5 km (80.5 %) are overhead lines, and 41.7 km (19.5 %) are cable lines. The electric network is fed by 11 transformer substations (one 110/10 kV and ten 35/10 kV substations). The electric network is fed by 201 transformer stations (10/0.4 kV) with a total installed capacity of 21 297 kVA. The network consists of 296 nodes and 306 branches. In the network model, the branches model the power lines and switchgear (circuit breakers and fuses), the nodes model the load locations, the branch lines and the connections of the modelled lines and switchgear. Power transformers are not modelled. The graph tree of the modelled electric network is shown in Fig. 10.

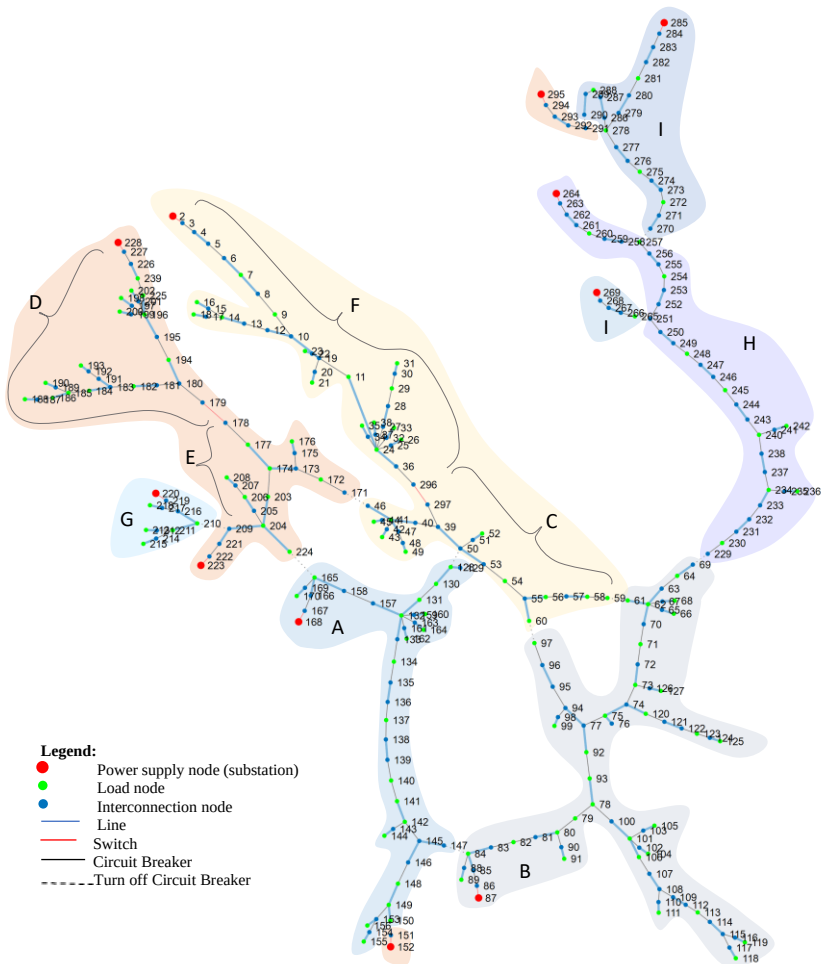


Fig. 10 Diagram of the 10 kV electric network showing the electric overhead and cable lines coming from various substations

The marked areas of the network under analysis (see Fig. 10) represent the normal mode connections of the electric network. The letters indicate the groups of consumers grouped according to the simulation results. The consumer nodes are divided into 9 groups, from A to I, according to the calculated disconnection frequency. The identified groups include the consumer nodes which are presented in Table 2.

Table 2 Consumer groups and consumer nodes in the network under analysis

No.	Consumer groups	Consumers nodes
1.	A	128, 130, 156, 155, 164, 144, 160, 141, 142, 162, 131, 132, 148, 150, 149, 165, 140, 137, 134, 170
2.	B	61, 62, 120, 75, 123, 125, 64, 127, 66, 68, 73, 118, 119, 71, 104, 113, 111, 106, 101, 105, 97, 99, 93, 78, 92, 84, 91, 80, 79, 89, 82
3.	C	45, 41, 43, 49, 56, 59, 60, 58, 52, 54
4.	D	194, 182, 184, 190, 186, 185, 188, 193, 225, 196, 202, 200, 239, 198
5.	E	208, 206, 172, 224, 204, 203, 176, 174, 177
6.	F	9, 33, 26, 11, 24, 29, 35, 38, 29, 31, 21, 7, 23, 14, 16, 18
7.	G	211, 210, 218, 213, 215
8.	H	230, 234, 236, 242, 240, 245, 248, 254, 260, 257
9.	I	272, 275, 278, 281, 288, 265

By using a combination of the Max Flow and Monte Carlo methods, the probabilistic indices are presented in Table 3 and shown graphically in Fig. 11 and Fig. 12.

Table 3 Indexes of supply reliability for different consumer groups for electric energy

Consumer groups	f, 1/m	Ta, h.	W*, %	W*, kWh	W_not supplied_group, kWh
A	8.35–8.29	3.21–1.039	0.379–0.027	3070–250	22992
B	7.70–7.66	2.69–1.019	1.328–0.047	6109–225	38153
C	7.00–6.93	3.43–1.045	1.234–0.044	3707–168	12929
D	6.25–6.23	4.58–1.204	0.726–0.009	8192–297	24018
E	4.23–4.21	5.83–1.066	1.442–0.009	2561–125.8	8173
F	3.18–3.17	4.36–1.051	7.728–0.025	3317–374	22284
G	1.38–1.37	8.43–1.056	0.145–0.001	1935–324	3991
H	0.92–0.92	5.62–1.000	0.111–0.001	1600–103.3	3779
I	0.15–0.09	1.030–1.000	0.004–0.001	67–17	219

Here: W*, % – electric energy not supplied at the end consumer;

W_not supplied_group, kWh – unsupplied electric energy for the whole group

The calculated SAIFI for the whole network under consideration (4,51 times/consumer) is higher than the one declared by the actual network operator (0,62 times/consumer), a discrepancy arising due to the fact that the model does not consider the 0,4 kV network and its fast (0,1 hour; 0,01 hour) switching of the automatic switches, which increases the reliability of the power supply to the end consumers.

The assessment of the SAIDI index also shows that these consumer's groups experience relatively low power outage times per consumer or consumer group (see Fig. 11 a). The expected disconnection times for each network consumer and consumer group are given in Fig. 11 b.

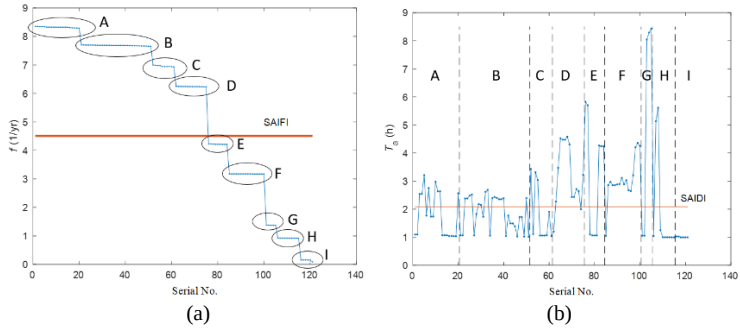


Fig. 11 Expected frequency of disconnection of consumers, times per year (a); Expected disconnection times per consumers, hours (b)

Considering the kWh per year of undelivered energy per consumers, as well as the duration of disconnections, consumers in Zone D will experience the highest shortfall (see Fig. 12). This zone is likely to experience problems with the reliability of the electric energy supply due to the non-supply of electric energy.

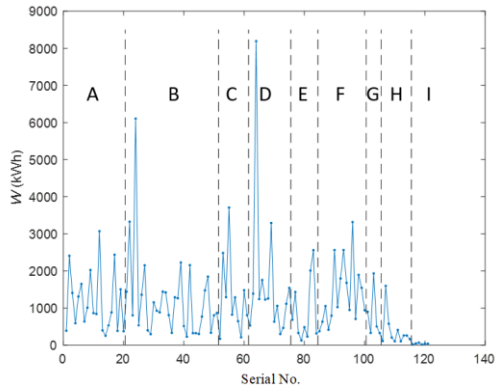


Fig. 12 Expected energy not delivered to each consumer, kWh/year

3.2. Analysis of the Reliability of Electric Energy Supply under Different Scenarios

By applying the Max Flow method, network states are generated, and optimal flow paths are calculated. The three scenarios selected for calculation and evaluation are:

- **Scenario A** – Overhead line sections are replaced by cable;

- **Scenario B** – Replacement of conventional manually-operated disconnectors with remotely-operated disconnectors with faster disconnection and/or switching to reduce the switching times;
- **Scenario C** – In order to quickly isolate a damaged line segment, smart line switches are installed.

Scenario A. When sections of overhead lines are replaced by cable, the change in the frequency of consumer disconnections decreases in proportion to the length of the cable (see Fig. 13).

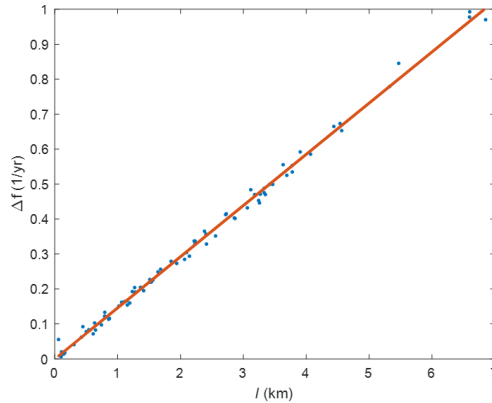


Fig. 13 Consumer disconnections are less frequent as a function of the length of the cabled line (calculated points and a line's approximation of those points $y = 0,1464x - 0,0004706$, $R=0.996$)

Fig. 14 *a* and *b* shows the change in the frequency of disconnection of network consumers and the duration of consumer disconnections when circuit overhead lines are replaced with a cable.

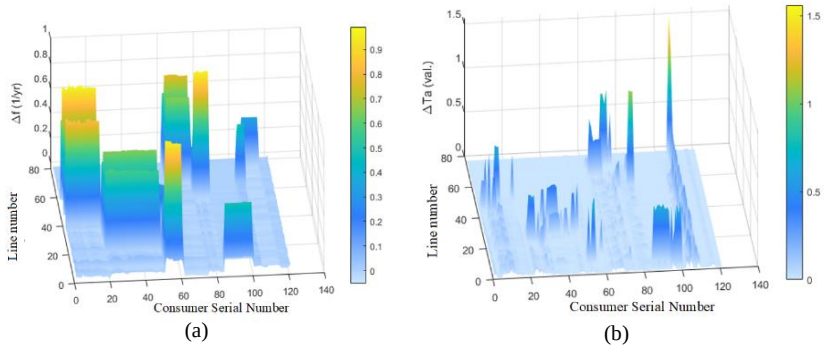


Fig. 14 After replacing overhead lines with a cable, there was a change in the frequency of consumer disconnections (a) and a change in the length of consumer disconnections (b)

The frequency of disconnections would be most reduced for consumers in groups A, C, D and E who are fed by long overhead lines. The expected duration of disconnection (see Fig. 14 (b)) would decrease the most for consumers in Groups E and G, by 1,1 and 1,5 hours respectively. The change in the amount of energy not supplied to consumers after replacing OL with cable is shown in Fig. 15.

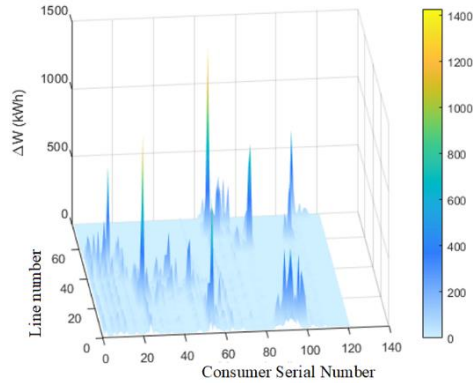


Fig. 15 Change in the amount of energy not supplied to consumer as a result of the installation of cables in place of overhead lines

As regards the amount of undelivered energy, the most sensitive were consumer groups B and D (see Fig. 15). Replacing one section of the overhead line with a cable would reduce the amount of undelivered energy to 5660 kWh per year.

Scenario B. The simulation results show that the replacement of the line interrupter switch by remotely controlled interrupter switch has no practical impact on the frequency of consumer disconnections (see Fig. 16 (a)). Depending on the type and length of the line, it can reduce the duration of disconnections due to switching by 0,1 to 0,9 hours, respectively.

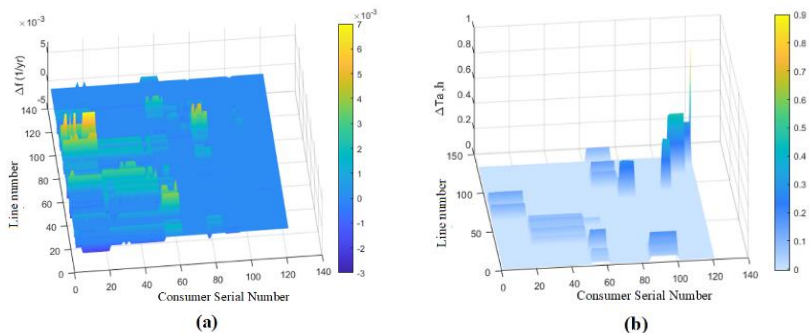


Fig. 16 Following the installation of remotely controlled line breakers, (a) change in the frequency and length of consumer disconnections was observed (b)

The most prominent positive effects would be achieved for consumers in groups E, G and H and I. For these groups, the expected reduction in disconnection time would be 0,3–0,5 hours. The amount of unused energy would be reduced to 2370 kWh/year with the installation of a single, remotely controlled interrupter switch. The change in the amount of energy not supplied to consumers with the installation of remotely controlled line interrupter switch is shown in Fig. 17.

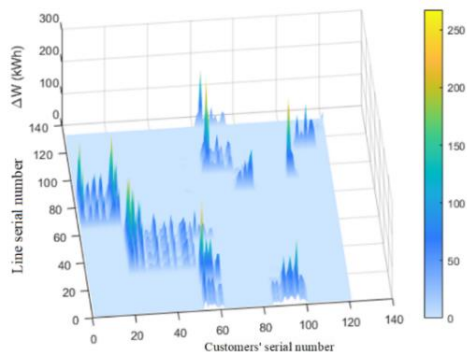


Fig. 17 Evolution of the amount of energy not supplied to consumers through the installation of remotely controlled line disconnectors

This group of consumers loses electric energy due to outages, but not due to faults ($T_a=2.69-1.019$)

Scenario C. In this scenario, smart line switches are installed. The change in the consumer disconnection frequency and the change in the consumer disconnection duration after the OL switches have been installed is shown in Fig. 18.

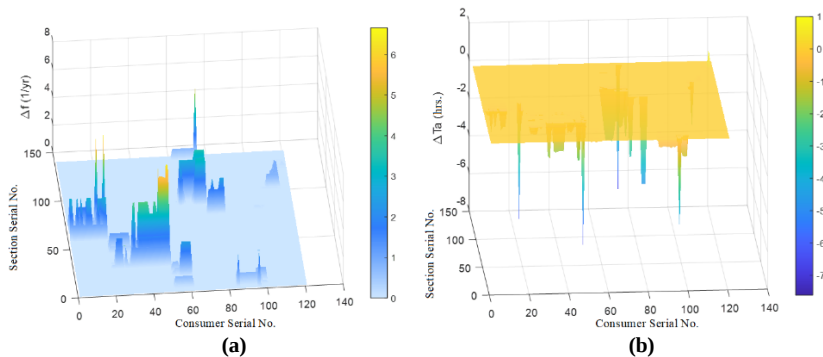


Fig. 18 Evolution of consumer disconnection frequency and duration of consumer disconnection after installation of overhead line circuit breakers

The installation of a single line breaker in the network in question reduces the amount of undelivered energy to 4220 kWh per year.

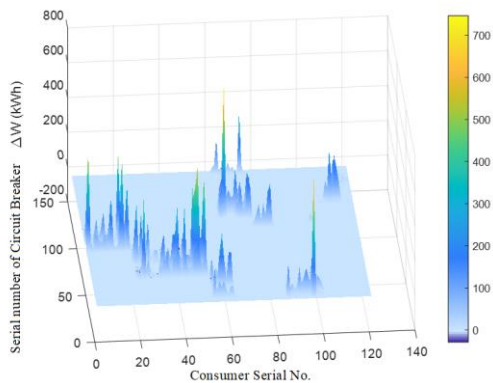


Fig. 19 Evolution of the amount of energy not supplied to consumer after the installation of circuit breakers

The results show that not all electric energy consumers will be affected by the introduction of smart devices. The most prominent change in the amount of undelivered energy will be achieved for consumers in groups A, B, C, D and E. The installation of a single line breaker on the network under consideration reduces the amount of undelivered energy to 4220 kWh per year.

3.3. Strategies for Enhancing the Supply Reliability of the Electric Distribution Network

In order to identify the most suitable reliability improvement actions, characteristic consumer nodes with lower reliability compared to other consumers have been selected. Furthermore, in order to improve the reliability of the power supply to these nodes, the impact of different technical measures and their combinations on the reliability indices has been examined. The impact of replacing such grid elements on the reliability of the nodes is analysed:

- a) installation of telecontrolled switches;
- b) replacement of the longest section of the overhead line by a cable;
- c) installation of a line breaker at the point of the switch;
- d) *b* and *c* options taken together;
- e) replacing the three longest sections of the overhead line with cables and installing a circuit breaker at the point of the interrupter switch.

Nodes 128, 164 and 132 in User Group A. The changes in reliability indexes are shown in Table 4. The data are compared with the initial network configuration.

Table 4 Reliability indexes for Consumer Group A consumers, 128, 164 and 132 Nodes

No.	Node 128			Node 164			Node 132			Network
	f , 1/m	T_a , h	ΔW , kWh	f , 1/yr	T_a , h	ΔW , kWh	f , 1yr	T_a , h.	ΔW , kWh	
0*	8.35	1.10	—	8.34	3.21	—	8.32	2.64	—	—
a)	8.35	0.96	48	8.34	3.07	56	8.32	2.50	160	2010
b)	7.38	1.08	52	7.35	2.67	350	7.34	1.98	1035	3420
c)	5.48	1.15	120	5.46	4.39	140	5.44	3.51	400	2415
d)	4.50	1.13	172	4.47	3.75	490	4.46	2.62	1435	5880
e)	3.42	1.14	220	4.28	3.42	600	3.41	2.83	1720	8110

Note: * – the initial data of the power network configuration

here: f – frequency of disconnections, 1/yr;

T_a – average duration of disconnection, hours;

ΔW – Reduction in the amount of energy not supplied to the node, kWh

The change in the replacement of the elements would increase the reliability of Node 128 by 59,05 %, Node 132 by 48,7 %, and Node 164 by 59,02 %. The change in reliability would increase by 87,2 % for Node 128, 25 % for Node 132 and 16,9 % for Node 164.

Nodes 61 and 75 in consumer group B. The reliability performance of these nodes is calculated with the following changes to the network elements:

- a) line 83-84 and line 69-229 interrupter switches shall be replaced by telemanagement interrupter switch to improve the switching efficiency;
- b) the longest sections of overhead lines 84–85, 100–101 and 74–75 (total length 12.3 km) shall be replaced with a cable;
- c) the interrupter switch 78–100 is replaced with a circuit breaker;
- d) options *b* and *c* shall be applied in combination, supplemented by the installation of a second circuit breaker in place of the 75–77 interrupter switch;
- e) replacement of the three longest sections of the overhead line: 132–157, 128–130, and 131–132 (total length 13.4 km) with a cable and the installation of a circuit breaker at the in the place of the 134-135 interrupter switch.

The results of the changes to the reliability indexes when network elements have been modified are shown in Table 5. The data are compared with the original network configuration.

Table 5 Reliability indexes for 61 and 75 Nodes in Consumer Group B

No.	Node 61			Node 75			Network
	$f, 1/\text{yr}$	T_{av}, h	$\Delta W, \text{kWh}$	$f, 1/\text{yr}$	T_{av}, h	$\Delta W, \text{kWh}$	$\Delta W, \text{kWh}$
0*	7.70	1.07	–	7.70	2.38	–	–
a)	7.70	0.97	140	7.70	2.28	265	2370
b)	5.90	1.05	360	5.89	2.00	2180	9210
c)	6.55	1.08	200	6.55	2.62	380	2795
d)	5.31	1.05	470	5.29	2.11	2380	9210
e)	2.27	1.01	1045	4.07	1.03	4715	20850

Note: * – the initial data of the power network configuration

Reliability indexes would be improved by 70,52 % at Node 61 and 47,2 % at Node 75. The change in the recovery time improvement is 9,3 % for Node 61 and 56,7 % for Node 75. The last network reconfiguration was found to be the most likely to improve the reliability of Nodes 61 and 75 (option e), replacing the three longest sections of the overhead line 132–157, 128–130 and 131–132 (total length 13.4 km) with cables and installing a circuit breaker at the site of the separator 134–135.

Nodes of D and E Consumers Groups: 184 ir 208

Table 6 Reliability indexes 184 and 208 for downstream Nodes of the D and E consumers groups

No.	Node 184			Node 208			Network
	$f, 1/\text{yr}$	T_{av}, h	$\Delta W, \text{kWh}$	$f, 1/\text{yr}$	T_{av}, h	$\Delta W, \text{kWh}$	$\Delta W, \text{kWh}$
0*	6.24	3.47	–	4.23	5.83	–	–
a)	5.47	3.82	300	4.23	5.83	0	2090
b)	4.08	3.49	2810	4.23	5.83	0	8560
c)	6.22	3.52	-80	3.00	7.93	25	2740
d)	4.16	3.56	2600	3.00	7.94	25	11340

Note: * – the initial data of the power network configuration

The reliability of Node 184 would improve by 34,6 %, whereas the failure rate of Node 208 would decrease by 29,07 %. However, the undelivered power values of the 208 Node remain sufficiently low for all technical solutions. The results and analysis show that cabling can significantly reduce the frequency of outages and the amount of undelivered energy. Cabling one end of a duplex power line, with a line interrupter switch, can lead to a slight deterioration in the reliability performance. However, the overall effect on the reliability of the power supply is positive. In addition, line cabling may increase the average disconnection time, due to the longer repair time of cable.

The Node 215 or Consumer Group G. The data is compared with the original network configuration (see Table 7)

Table 7 Reliability indexes for Node 215 of Consumer Group G

No.	Node 215			Network
	$f, 1/\text{yr}$	T_{av}, h	$\Delta W, \text{kWh}$	$\Delta W, \text{kWh}$
0*	1.37	8.43	–	–
a)	1.41	8.16	0	0
b)	0.42	10.9	180	1100

Note: * – the initial data of the power network configuration

Only the replacement of the entire network up to the point of separation with a cable network has an impact on the failure rate of Node 215. The failure rate would improve by 69,3 %. To improve the repair time, a tele-controlled interrupter switch would be useful to isolate the damaged branches more quickly: 212–213 and 217–218. To improve the indexes value would only improve by 3,2 %.

The results of the analysis show that the installation of tele-managed interrupter switches can reduce the average disconnection time to 8,2 hours, but would result in a slight increase in the frequency of disconnections. Cabling the whole network would reduce the change in the disconnection rate to 0,42 times per year, but would further increase the average disconnection time to 10,9 hours. In order to reduce the disconnection time, it would be appropriate to install a redundant power supply.

3.4. Results of Implementing Strategies by using the Game Theory Approach

The Game Theory decision is applied to assess the decisions of the interests of the Lithuanian EDN and electric energy consumers. The game involves two players: the STO and the electric energy consumer. The game is based on the electric network and the investment and price paid for the electric energy supply. The players' areas of evaluation are shown in Table 8. One of the players who does not respect the general rules is the loser. With the prevalence of common rules and a penalty system, a player is likely to suffer financially when the rules are broken.

Table 8 Areas for DSO and electric energy consumers to be evaluated

DSO		Choices
Investing in network quality	Recruitment of additional workforce	+
Consumer		
Getting a good quality supply of electric energy	Consumers are guaranteed a rapid restoration of the grid, with power restoration carried out in accordance with the agreed contracts	+

In order to find the best solutions, it is necessary to evaluate the best option for a strategy when the opponent's option is known (see Table 9).

Table 9 Probabilistic network states

Players	Stage of network							
	1 st State		2 nd State		3 rd State		4 th State	
	Change and renew the electric network	Guaranteed workforce	Investment and replacement of electric energy network elements, part of the network	Guaranteed workforce	Investment and replacement of electric network elements, part of the network	Secure workforce	Investment and replacement of electric network elements, part of the network	Secure workforce
DSO	+	+	-	+	+	-	-	-
	Getting quality of electric energy supply	Fast restoration	Getting quality of electric energy supply	Fast restoration	Getting quality of electric energy supply	Fast restoration	Getting quality of electric energy supply	Fast restoration
Consumer	+	+	-	+	+	-	-	-

Based on the potential strategies in Table 9, three different conditions are adopted in each situation:

- **Scenario 1.** Evaluate the schemes shown in Fig. 7 and Fig. 8 by changing the network indexes;

- **Scenario 2.** Evaluate the schemes shown in Fig. 7 and Fig. 9 with changes to the network indexes;
- **Scenario 3.** The schemes in Fig. 8 and Fig. 9 are evaluated against each other.

It is assumed that the loads are similar in all schemes: $V_1 = V_2 = V_n$, and the arrangement of the linear loads is the same. Taking into account the network states (see Table 9) and the different network topologies, the results of the calculations are shown in Fig. 20.

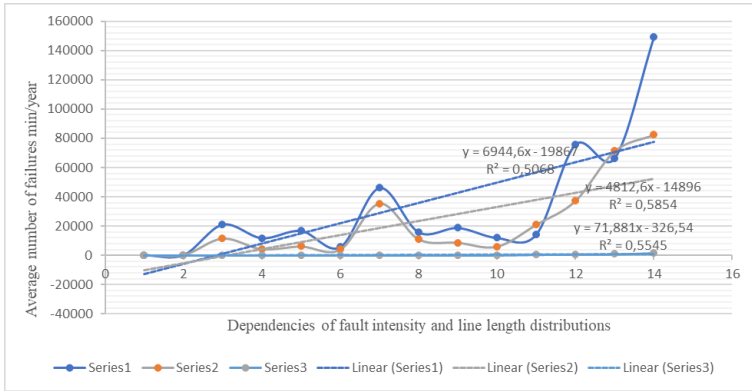


Fig. 20 Probability distribution of fault intensity in different power schemes

All power plant schemes have different disconnection times due to the structure of the network and the equipment installed on it. The probability of failures in the third scheme is clearly visible when the intensity of failures is higher than $\lambda = 0.5$, otherwise the number of failures over the 50 simulated years is very low and below 1 %/ 1 km.

Scenario 1. Based on the game conditions in Table 9, when the network states change as a result of changes, modernisation or changes in the topology of the electric network, a game is in progress. The distribution of the game scenarios and the results are presented in Table 10.

Table 10 Analysis of electrical circuits by using Game Theory: Scenario 1

	Levels of strategies	Strategy choice		Price allocation, Eur.	
		B			
A	L_1 H_1	L	H	L	H
		9.6	6	240 Eur.	122.4 Eur.
		8	10.8	200 Eur.	242.4 Eur.

$MiniMax = (10)$; $MaxiMin = [8]$, column $MiniMax \neq$ row $MaxiMin$, there is no saddle point in this game, and there is no course of action which would be more important than the other.

Scenario 2. When analysing the situation from the perspective of one of the players, there is an opportunity to seek higher labour supply or to invest more in EDN, either through the introduction of new technologies or through a change in the network topology. The power plant schematics in Fig. 7 and Fig. 9, their disconnection, reconnection and repair times are assessed, and the results are presented in Table 11.

Table 11 Analysis of electrical circuits by using Game Theory: Scenario 2

	Levels of strategies	Strategy choice		Price allocation, Eur.	
		B			
A	L_I H_I	L	H	L	H
		9.6	4.92	240 Eur.	120.12 Eur.
		8	16.8	200 Eur.	134.52 Eur.

$MiniMax = (10)$, $MaxiMin = [5]$; Column $MiniMax \neq$ Row $MaxiMin$. Game value $V=8.53$.

Scenario 3. This scenario uses the power plant schematics shown in Figures 8 and 2.7. In an old, deteriorated power grid, the level of fault intensity naturally rises, but line breaks on this network would have a much lower impact compared to the network topology in Fig. 9. In such a network, the fault intensity has to be more than 50 % per line kilometre in order to estimate the number of disconnections. The distribution of possible scenarios for the game is shown in Table 12.

Table 12 Analysis of electrical circuits by using Game Theory: Scenario 3

		Levels of strategies		Strategy choice		Price allocation, Eur.	
				B			
A	L_1 H_1	L H		L	H		
		6	4.802	122.4 Eur.	120 Eur.		
		10.8	16.8	242.4 Eur.	134.52 Eur.		

Column $MiniMax =$ Row $MaxiMin = 11$. The optimal solution is also shown by the economic expression of the value of the network scheme, conditional on the reduction of the restoration time when the switching time is reduced.

Game Theory scenarios can be chosen in different ways, depending on the desired outcome. The gamification approach allows for appropriate decisions to be made to ensure the security and reliability of electric energy supply, while taking into account the costs in terms of outage, restoration and

switching times which have a significant impact on the electricity price levels affected. The Game Theory approach is very useful for understanding and predicting the electric energy consumer behaviour patterns, while taking into account the price fluctuations and other factors.

RESULTS

1. The methodology for assessing the reliability of the electric distribution network, which includes criteria for assessing the reliability of the network, allows the evaluation and identification of the status of the electric network, the reliability of the supply, and the amount of electric energy that is expected to be not supplied to each electric energy consumer. In order to increase the reliability of the electric network and to obtain an optimal solution, the specific topology areas of the electric distribution network and their technical performances have to be assessed and the appropriateness of the changes to the electric network is based on the technical and economic impact on the reliability of the power supply..
2. An algorithm based on the Monte Carlo and Max Flow methods which do not require detailed data on the electric network simplifies the determination of indexes of the reliability of the power supply and energy availability to consumers. Using this algorithm and the technical data of the electric distribution network, the reliability and capacity aggregates of its elements and the electricity demand of the consumers, the values of the reliability indexes can be improved by up to 87 % by changing the topology of the network and by modernising the network.
3. An algorithm for making optimal decisions on the suitability of electric network modifications, using Game Theory, allows to assess the importance of various factors in relation to the electric energy consumer's need for sufficient electric energy and the reliability of its supply. The decision-making process for modifying the electric distribution network would increase the reliability of the electric network by up to 70 %..
4. After applying the developed reliability assessment methodology to the 10 kV electric distribution network under consideration, it was found that: replacing a 1 km overhead line with a cable allows to reduce the expected intensity of disconnection of consumers by up to 14 %, and the amount of undelivered energy per year - by up to 3,2%; the highest reliability of power supply is obtained by complex optimisation of the network topology, replacing the overhead lines with cable and installation of smart overhead line circuit breakers. The expected disconnection time can be reduced to 1,5 hours, the amount of undelivered energy can be reduced by up to 51 % per year and the switching time can be reduced by 0,9 hours.

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INFORMATION ABOUT THE AUTHOR

Gintvilė Šimkonienė was born on the 20th of March, 1987 in Druskininkai, Lithuania. She lived in Varėna from birth until the beginning of her studies. In 2006 she graduated from Varėnos „Ryto“ secondary school and at the same time graduated from the National Academy of School Students ("NMA"), at Kaunas University of Technology Gymnasium. She graduated in 2010 with a Bachelor's degree in Electrical Engineering and in 2012 with a Master's degree in Electric Power Engineering from the Department of Electrical Systems, at Kaunas University of Technology. In 2012-2022 doctoral studies at KTU Technological Science, Energetics and Power Engineering (06T). Since 2012 she has been working as a lecturer/assistant - laboratory assistant at KTU, Department of Electrical Systems. From 2013-2014 she worked as an assistant in Lithuanian Maritime Academy. From 2014 until today she has been working as a lecturer and from 2021 as Head of the Study Program “Marine Electrical and Electronic Engineering” in Lithuanian Maritime Academy.

REZIUMĖ

Darbo aktualumas

Europos Sąjungoje veikia 2400 elektros skirstomųjų tinklų įmonių, prie elektros skirstomųjų tinklų prijungę 260 milijonų vartotojų, iš kurių 99 % yra buitiniai vartotojai ir mažos įmonės. Lietuvos elektros skirstomųjų tinklų (toliau EST) ilgis siekia daugiau kaip 126 600 km, didžioji (98,5 %) tinklo dalis yra užmiesčiuose ir mažuose miesteliuose. Tinkle vyrauja 94 % 10 kV oro linijos. Šiandien dauguma Lietuvoje eksploatuojamų 0,4–35 kV elektros skirstomojo tinklo ir jo komponentų tarnavimo laikas viršija daugiau kaip 30 metų. Gedimai, elektros tinklo pralaidumo nebuvimas ir perdavimo pajėgumo trūkumas, ilgas elektros energijos remonto ir atkūrimo laikas, dideli energetiniai nuostoliai apsunkina elektros energetikos sistemos darbą. Skirstomojo tinklo sistema pasižymi pasyvia charakteristika, o nuolat atsirandantys gedimai, turintys įtakos elektros energijos persiuntimo kokybei ir patikimumo rodiklių vertėms, neužtikrina elektros tiekimo kokybės, nepatenkina vartotojų poreikių.

Lietuvos EST patikimumui vertinti nuo 2012 m. pateikiami fiksuoti elektros tinklo gedimų ir nutrūkimų duomenys nėra tikslūs, patikimi, dėl to vertinimas ir rezultatai neatspindi realios EST situacijos. Tinklo patikimumas vertinamas abstrakčiai, probleminės srities sprendimo metodika taikoma visam Lietuvos EST. Šiuo metu taikoma skaičiavimo metodika neišsprendžia silpniausių elektros tinklo sistemos dalių, elektros vartotojų pasitenkinimo lygio ir patikimumo lygių reikalavimų užtikrinimo. Situaciją apsunkina ir ES šalių EST patikimumo vertinimas. Iki šiol Europos Sąjungos šalys neturi bendro sutarimo, kaip skaičiuoti EST patikimumą taikant vienodus rodiklius, kurie būtų vienodo turinio ir būtų palyginami. Nėra bendrų ir konkrečių priemonių, iš esmės sprendžiančių vyraujančias problemas, nutraukimų registravimo taisyklių, aiškiai apibrėžtų normų, kokybės standartų, bendros ir vieningos skaičiavimo metodikos. ES šalys skirtingai identifikuoja elektros tinklo nutraukimus ir gedimus, taiko skirtingas elektros tinklo gedimų ir nutraukimų duomenų kaupimo metodikas, o patikimumo vertinimą apsunkina skirtingi tinklų techniniai parametrai. Šalys taiko savo turimus ir reglamentuotus EST patikimumą vertinančius rodiklius, atsižvelgusios į techninius parametrus, toje šalyje reglamentuotą nutraukimo ir atkūrimo laiką.

Siekiant EST didesnio patikimumo, elektros energijos nenutrūkstamo tiekimo, reikalingas nuolatinis elektros tinklo stebėjimas ir analizė, identifikuojant elektros tinklo pažeidžiamiausias zonas, gedimų dažnį ir gedimų intensyvumą, nepateiktos elektros energijos kiekį vartotojams, parenkant tinkamus technologinius sprendimus ir patikimumą vertinančią metodiką.

Darbo tikslas. Sukurti elektros skirstomojo tinklo vertinimo metodiką, leidžiančią įvertinti pažeidžiamiausias tinklo zonas, ir jo modernizavimo poreikį, siekiant pagerinti patikimumo rodiklius, esant neapibrėžtiems elektros tinklo gedimų duomenims.

Darbo uždaviniai:

1. Sudaryti elektros skirstomojo tinklo patikimumo vertinimo metodiką, kurioje parinkti patikimumą vertinantys kriterijai, skaičiavimo algoritmai, leidžiantys įvertinti skirtingų veiksnių įtaką patikimumo rodikliams ir parinkti optimalius sprendinius elektros tiekimo patikimumui padidinti;
2. Sukurti elektros tinklo patikimumo vertinimo algoritmą, panaudojant maksimalaus srauto metodą elektros tiekimo patikimumui vertinti;
3. Sukurti elektros tinklo modernizavimo tikslingumo įvertinimo algoritmą, leidžiantį įvertinti skirtingus veiksnius, priimant sprendimą modifikuoti elektros tinklą;
4. Pritaikyti sukurta patikimumo vertinimo metodiką priimant optimalius sprendinius, įvertinant elektros skirstomojo tinklo modernizavimo tikslingumą patikimumui padidinti.

Mokslinis darbo naujumas. Sukurta elektros skirstomojo tinklo patikimumo vertinimo metodika, paremta Monte Karlo ir maksimalaus srauto algoritmais, išplečia galimybes įvertinti elektros energijos tiekimo patikimumo rodiklius, kai elektros tinklo topologija yra keičiama. Žaidimų teorijos metodas leidžia nustatyti tinkamiausią abipusį žaidėjų strategijos pasirinkimą, įvertinus elektros tiekimo avarijų atvejus. O kompleksinis metodų taikymas suteikia išsamesnį ir patikimesnį elektros tinklo patikimumo rodiklių įvertinimą.

Praktinė darbo vertė. Sukurta elektros skirstomojo tinklo patikimumo vertinimo metodika, leidžianti įvertinti elektros tinklo patikimumą, pralaidumą bei elektros energijos tiekimo galimybę vartotojams. Taikant šias skaičiavimo metodikas, galima prognozuoti tinklo gedimus, analizuoti skirtingas tinklo konfigūracijas bei priimti efektyvesnius elektros tinklo planavimo sprendimus, kurių rezultatas – pagerintas elektros tinklo patikimumas ir nepertraukiamas elektros energijos tiekimas vartotojams. Tai gali būti naudinga elektros tinklo operatoriams, siekiant greičiau reaguoti į avarines situacijas, tinkamai planuoti tinklo konfigūracijas ir priimti strateginius sprendimus, kartu užtikrinti patikimą elektros energijos tiekimą vartotojams, mažinti elektros energijos tiekimo sąnaudas.

Ginamieji disertacijos teiginiai:

1. Sudaryta elektros skirstomojo tinklo patikimumo vertinimo metodika leidžia techniniu ir ekonominiu aspektais įvertinti elektros tiekimo patikimumo pokyčius, įdiegus skirtingus sprendinius.
2. Elektros tiekimo patikimumui įvertinti gali būti taikomas maksimalaus srauto metodas.
3. Sprendimų modifikuoti elektros tinklą, siekiant padidinti elektros tiekimo patikimumą, priėmimui pagrįsti gali būti naudojama žaidimų teorija.
4. Sukurta patikimumo vertinimo metodika leidžia parinkti optimalius elektros skirstomojo tinklo modernizavimo sprendinius, atsižvelgiant į sprendinių techninę ir ekonominę įtaką elektros tiekimo patikimumo pokyčiams.

Darbe taikomi metodai. Daktaro disertacijoje taikomi metodai buvo parinkti atsižvelgiant į tyrimo tikslus ir turimų duomenų kiekį. Darbe taikomi šie metodai:

- Teoriniam pagrindimui atlikta sisteminė literatūros ir dokumentų analizė: atlikta detali palyginamoji mokslinės literatūros ir dokumentų analizė, siekiant išanalizuoti patikimumo sampratos reikšmę, patikimumą vertinančius rodiklius ir taikomus metodus.
- Skaičiavimų metodai: Skaičiavimams naudojamos *MATLAB* ir *Python* modeliavimo programos, kurios leidžia atlikti patikimumo vertinimo skaičiavimus ir simuliacijas.
- Atliktas duomenų sutvarkymas, jų grupavimas, sisteminimas, analizė ir apdorojimas, naudojant programinę „*Microsoft Office*“ paketą, „*MATLAB Plotting*“ biblioteka nubraižyti grafiniai vertinamieji metodai.

Darbo aprobavimas. Mokslinių tyrimų disertacijos tema rezultatai pristatyti 7-iose tarptautinėse konferencijose (3-iose užsienyje organizuotose tarptautinėse konferencijose), svarbiausi tyrimų rezultatai paskelbti 5-iose moksliniuose straipsniuose, išspausdintuose recenzuojamuose tarptautinėse duomenų bazėse esančiuose periodiniuose mokslo leidiniuose.

Disertacijos struktūra ir apimtis. Daktaro disertaciją sudaro: įvadas, literatūros apžvalga, tyrimo metodika, tyrimo rezultatai, aptarimo dalys ir išvados, literatūros šaltinių sąrašas, autorės mokslinės ir kūrybinės veiklos aprašymas (*Curriculum vitae*), straipsnių ir mokslinių konferencijų sąrašas, padėka ir priedai. Disertacijos apimtis – 127 puslapiai. Disertacijos pagrindinėje

dalyje yra 67 paveikslai, 32 lentelė ir 155 cituojamųjų literatūros šaltinių sąrašas, 9 priedai.

IŠVADOS

1. Sudaryta elektros skirstomojo tinklo patikimumo vertinimo metodika, apimanti tinklo patikimumo vertinamusius kriterijus, leidžia įvertinti ir identifikuoti elektros tiekimo patikimumą ir tikėtina nepatiktos elektros energijos kiekį kiekvienam elektros energijos vartotojui. Siekiant padidinti tinklo patikimumą ir norint gauti optimalų sprendinį, reikia įvertinti elektros skirstomojo tinklo konkrečias topologijų zonas ir jų techninius išpildymus, o elektros tinklo modifikavimo tikslingumas grindžiamas atsižvelgiant į techninę ir ekonominę įtaką elektros tiekimo patikimumui.
2. Algoritmas, pagrįstas Monte Karlo ir maksimalaus srauto metodais, kurie nereikalauja detalių duomenų apie elektros tinklą, supaprastina elektros tiekimo patikimumo ir energijos prieinamumo vartotojams rodiklių nustatymą. Naudojant šį algoritmą ir elektros skirstomojo tinklo techninius duomenis, jo elementų apibendrintus patikimumo bei pralaidumo rodiklius ir vartotojų elektros energijos poreikį, keičiant tinklo topologiją ir atliekant tinklo modernizavimą, patikimumo rodiklių vertes galima pagerinti iki 87 %.
3. Algoritmas, skirtas optimaliems sprendimams priimti, dėl elektros tinklo modifikavimo tikslingumo, naudojant žaidimų teoriją, leidžia įvertinti įvairių veiksnių svarbą pasirenkant tinkamus sprendimus, atsižvelgiant į elektros vartotojo poreikius, pakankamą elektros energijos kiekį ir jo tiekimo patikimumą. Elektros skirstomojo tinklo sprendimų priėmimas modifikuoti elektros tinklą patikimumą padidintų —iki 70 %.
4. Pritaikius sukurtą patikimumo vertinimo metodiką nagrinėjamam 10 kV elektros skirstomajam tinklui, nustatyta, kad: 1 km oro linijos pakeitimas kabeline leidžia sumažinti tikėtiną vartotojų atjungimo intensyvumą iki 14 %, o nepatiktos energijos kiekį per metus – iki 3,2 %; didžiausias elektros energijos tiekimo patikimumas gaunamas kompleksiskai optimizuojant tinklo topologiją, keičiant oro linijas kabelinėmis ir įrengiant išmaniuosius oro linijų jungtuvus. Tikėtina atjungimo trukmė gali būti sumažinama iki 1,5 val., nepatiktos energijos kiekis sumažėtų iki 51 % per metus, o komutacijų trukmė – 0,9 val.

UDK 621.316.1-192+519.2+519.83] (043.3)

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