RIGA TECHNICAL UNIVERSITY
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METHODS OF CALCULATION OF ELECTRIC DISTRIBUTION NETWORK RELIABILITY AND THEIR REALISATION

Summary of the Doctoral Thesis

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DOCTORAL THESIS
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To be granted the scientific degree of Doctor of Engineering, the present Doctoral Thesis will be publicly presented on 11th February 2016 – 12:00 am, at the Faculty of Power and Electrical Engineering of Riga Technical University, 12/1 Azenes Street, Room 306.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to any other scientific degree.

Laila Zemite …………………………….(Signature)

Date: ………………………

The present Thesis has been written in the Latvian language; it comprises an introduction, five chapters, conclusions and proposals, bibliography and six appendices. The total volume of the Thesis is 174 pages, it is illustrated by 35 tables and 36 figures. The bibliography lists 117 literary sources.

CONTENTS

TOPICALITY OF THE SUBJECT OF THE DOCTORAL THESIS

With the development of economy and mankind, the electric distribution networks and technical and technological solutions of the equipment connected to them are also changing resulting in the changes of their application opportunities and requirements to quality of the supplied energy. Therefore, in Latvia the development of economy leads to the increasing demands of customers to the reliability of electricity supply. The basic task of an electric supply network operator is to provide a customer with energy supply of a necessary level of reliability and quality with as low financial expenses as possible. The evaluation of interruptions risks of an electric supply system requires one to know structure of the network, its load and customers' data [3]. In 90 % of all the electric energy failures, the problem of energy supply reliability is at the level of distribution networks — in the elements of the supply network (overhead lines, cables, transformer substations, breakers, switches, etc.); therefore, the improvement of the distribution network reliability is a question of top importance [13]. The present research is devoted to the distribution networks in general and the 20 kV networks that compose the largest part of all Latvian networks in particular [1].

The level of automation of Latvian networks is still not enough. The parameters of interruption frequencies and duration by JSC Sadales tīkls are still behind the average level of the European countries. In Latvia, in the result of interruptions power supply is interrupted significantly more customers, because it is not technically impossible automatically separate the rest part of the network into smaller interrupted sections and restore power supply in unaffected parts of the network [5]. Fast and efficient localisation of the interruptions and interruption influence onto a small number of customers requires an increase in the number of the network sectioning elements and estimates their optimal place. Improvement of the sectioning opportunities and reducing of the interruption number resulting from the interruptions require additional sectioning elements in the network [1]. Taking into account the conditions of the free market and increasing demands of the customers in an uninterrupted electric power supply, the effectiveness of capital investments is expected to be determined as well as losses resulting from the supply interruptions and electric supply reliability should be calculated [5].

A great contribution to the solution of the electric supply reliability questions has been made by such well-known scientists as R. Billinton, R. E. Brown, Dr. habil. sc. ing. Zigurds Krišāns, Dr. sc. ing. J. Gerhards and others. In recent years, a lot of studies have been devoted to the investigation of electric supply reliability issues in Latvia, e.g.:

1) Kutjuns, Antons. Development of the Methodology to Estimate Electric Supply Reliability Factor. DOCTORAL THESIS. Riga: [RTU], 2006. 112 p.
2) Runčs, Jānis. Selection and Justification of the Variants of Urban Middle Voltage Networks Development. DOCTORAL THESIS. Riga: [RTU], 2007. 94 p.
3) Lvovs, Aleksandrs. Development of Methodology for Power Supply Reliability Level Performance-Based Regulation. DOCTORAL THESIS. Riga: [RTU], 2013. 156 p.

THE GOAL AND OBJECTIVES OF THE DOCTORAL THESIS

The following goal of the Doctoral Thesis has been set — to increase the electric supply reliability level taking into account the losses resulting from the number of sectioning elements and results of the electric supply reliability calculations.

The main objectives of the Doctoral Thesis are:

1) to develop methods for calculation of 20 kV distribution network reliability and its improvement solutions with a changing number of placement of sectioning elements and to develop methods for the calculation of losses resulting from 20 kV distribution network supply interruptions;

2) to structure the information obtained during the process of investigation and to analyse 20kV distribution networks for their further application in the development of calculation methods;
3) to calculate electric supply reliability, optimal number of sectioning elements and their localisation and losses resulting from the supply interruptions and analysis of results.

TOOLS AND METHODS OF THE RESEARCH

The present research analyses and summarises the information sources from available databases, books, publications in the English, Russian and Latvian languages.

The Doctoral Thesis is based on the calculation of electric supply reliability, analysis of empirical and statistical calculation of losses from the supply interruption and electric supply reliability optimisation, estimation of method development and applicability.

To achieve the objectives of the Doctoral Thesis, the methodology has been elaborated to calculate electric supply reliability and losses resulting from the interruptions of the supply; computer programs and software to perform the calculation have been developed, as well as the data have been calculated and analysed on the basis of software. Microsoft Excel software has been applied for the calculations and comparison and analysis of the data.

SCIENTIFIC NOVELTY OF THE DOCTORAL THESIS

Novelty of the Doctoral Thesis:

1) a detailed analysis has been provided, comparison of the calculation methods has been performed for the electric supply reliability, losses from the supply interruptions and number of sectioning elements and localisation, as well as the advantages and disadvantages have been identified;
2) the developed methodologies contain calculations of the electric supply reliability and losses resulting from supply interruptions based on A-Star, Monte Carlo modelling and genetic algorithm.
3) the developed methodologies allow optimal localisation and effectiveness of the sectioning elements as well as reducing the interruption duration, leading to minimisation of customer’s interruption, losses of the network and economy, and minimisation of electric supply system interruption elimination, capital and maintenance expenses.

PRACTICAL SIGNIFICANCE OF THE RESEARCH

The practical importance of the research is as follows:

1) the developed methods provide an opportunity to calculate reliability of the electric supply, losses after the interruption and the effectiveness and localisation of the sectioning elements;
2) the number and localisation of the sectioning elements are estimated and economically proved. The calculated number of the elements and their localisation can provide maximum effect with minimum capital expenses increasing the reliability of the electric supply, reducing the losses resulting from the interruptions and the duration of the interruption;
3) the application of the methods allows calculating and forecasting the level of the losses after the interruptions for the distribution networks, society and customers that are important for the estimation of a possible compensation value;
4) these methods can also be applied for the preliminary estimation of the effectiveness of capital expenses of JSC Sadales tīkls;
5) the methods of electric supply reliability and the calculation of number and localisation of the sectioning elements as well as of losses resulting from the supply interruptions can be

applied in practice not only under the Latvian conditions and for 20 kV distribution networks but in other states and for other rated voltage levels as well.

The results of the research are applied by JSC Sadales tīkls in the processes of planning and implementation of transition from the model of organisation of double-level operation to a single model, as well as in the planning of interruption prevention and preliminary estimation of effectiveness of capital expenses.

APPROBATION OF THE DOCTORAL THESIS

The results of the research have been reported and discussed at 7 international conferences:

1) Zemīte, L., Gerhards, J. Evaluation of Distribution Network Customer Outage Costs. *50th International Scientific Conference on Power and Electrical Engineering*, Latvia, Riga, October 2009 (EBSCO, CSA/ProQuest, VINITI, ISSN 1407–7345).
2) Kutjuns, A., Zemīte, L. Power Network System Reliability and Methods of Calculation. *IEEE Bucharest Power Tech*, Rumania, Bucharest, June 2009 (IEEE Xplore, SCOPUS, ISI, INSPEC).
3) Zemīte, L., Gorobecs, M., Gerhards, J., Ribickis, L., Ļevčenkovs, A. A–Star Algorithm for Reliability Analysis of Power Distribution Networks. *The 5th International Conference on Electrical and Control Technologies (ECT2010)*: Conference Proceedings, Lithuania, Kaunas, 6–7 May 2010. (SCOPUS, ISSN 1822–5934).
4) Kutjuns, A., Zemīte, L., Bērziņa, K. Practical and Theoretical Methods of Reliability Securing in Transmission and Distribution Network. *Proceedings of the 11th International Scientific Conference Electric Power Engineering 2010*, the Czech Republic, Brno, 4–6 May 2010. (SCOPUS, EBSCO, CSA, Ulrich’s International Directory, CEPS, OCLS).
5) Zemīte, L., Gerhards, J. Reliability Evaluation of Distribution Systems. *9th International Conference on Electrical and Control Technologies* (ECT–2014), Lithuania, Kaunas, 8–9 May 2014. (SCOPUS, ISSN 1822–5934).
6) Zemīte, L., Gerhards, J., Gorobecs, M., Ļevčenkovs, A. Optimization of Switch Allocation in Power Distribution Systems. *DEMSEE 2015 proceedings*, Hungary, Budapest, 24–25 September 2015. (Trivent Publishing, SCOPUS, ISBN 978–615–80340–0–5).
7) Zemīte, L., Gerhards, J., Gorobecs, M., Ļevčenkovs, A. Optimization of Distribution Systems Reliability with the Stochastic Behavior. Proceedings of 56th International Scientific Conference of Riga Technical University, Latvia, Riga, 14 October 2015. Riga: RTU Press, 2015. (IEEE Xplore, SCOPUS).

Publications

The results have also been presented in peer reviewed journals and conference proceedings:

1) Zemīte, L., Gerhards, J. (2009). Evaluation of Distribution Network Customer Outage Costs. *50th International Scientific Conference on Power and Electrical Engineering*, Latvia, Riga (EBSCO, CSA/ProQuest, VINITI, ISSN 1407–7345).
2) Kutjuns, A., Zemīte, L. (2009). Power Network System Reliability and Methods of Calculation. *IEEE Bucharest Power Tech*, Rumania, Bucharest (IEEE Xplore, SCOPUS, ISI, INSPEC).
3) Zemīte, L., Gorobecs, M., Gerhards, J., Ribickis, L., Ļevčenkovs, A. (2010). A–Star Algorithm for Reliability Analysis of Power Distribution Networks. *The 5th International Conference on Electrical and Control Technologies (ECT2010)*: Conference Proceedings, Lithuania, Kaunas (SCOPUS, ISSN 1822–5934).
4) Kutjuns, A., Zemīte, L., Bērziņa, K. (2010). Practical and Theoretical Methods of Reliability Securing in Transmission and Distribution Network. *Proceedings of the 11th*

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5) Zemīte, L., Gerhards, J. (2014). Reliability Evaluation of Distribution Systems. *9th International Conference on Electrical and Control Technologies* (ECT–2014), Lithuania, Kaunas (SCOPUS, ISSN 1822 –5934).
6) Zemīte, L., Gerhards, J., Gorobecs, M., Ļevčenkovs, A. (2015). Optimization of Switch Allocation in Power Distribution Systems. *DEMSEE 2015 proceedings*, Hungary, Budapest (Trivent Publishing, SCOPUS, ISBN 978–615–80340–0–5).
7) Zemīte, L., Gerhards, J., Gorobecs, M., Ļevčenkovs, A. (2015). Optimization of Distribution Systems Reliability with the Stochastic Behavior. *Proceedings of 56th International Scientific Conference of Riga Technical University*, Latvia, Riga (IEEE Xplore, SCOPUS).

STRUCTURE AND CONTENT OF THE DOCTORAL THESIS

The present Thesis has been written in the Latvian language; it comprises an introduction, five chapters, conclusions and proposals, bibliography and six appendices. The total volume of the Thesis is 174 pages; it is illustrated by 35 tables and 36 figures. The bibliography lists 117 literary sources.

1. ANALYSIS OF ELECTRIC SUPPLY RELIABILITY

The basic task of an electric supply network is to provide customers with uninterrupted and qualitative electric energy with as low financial expenses as possible. There are different variants of the definition of reliability .

In accordance with ISO 9000–2007 A/L standard, reliability is an ability of an element to complete particular functions at a particular time. Reliability can be described with probabilistic characters of availability or incapacity. Usually for the calculations of the network reliability such parameters as frequency and duration of customers' interruption from the supply system are considered. The parameters of the network reliability can reflect either the load reliability that describes the operation of all the elements or the reliability of the whole supply system operation. The parameters of loads allow calculating the reliability at any points [17].

In most cases, the electric supply reliability calculation methods use the calculation of the incapacity probability, average duration of it and duration of the electric energy restoration, duration of the element repairing and changing, localisation and time till interruptions.

The losses resulting from the electric supply breaking can be divided into three levels: those of distribution network, customers and social; each has its own conditions and priorities [12, 31]. For the calculation of total value of these losses, the losses due to the interruptions should be considered at all levels [6, 28].

1.1. Methods of Calculation of the Reliability of Electric Supply Network

The methods for electric supply reliability calculations could be divided into three basic categories: according to the type of calculation, according to the influencing factors and according to the optimisation of the electric supply reliability (Fig.1.1) [6, 14, 23, 27, 28, 41, 42, 43, 44].

In the network methods, the reliability diagrams are gradually transformed into simple parallel or series connections. Determining logically possible condition of the system and using equations of the parallel or series connections the necessary parameters of reliability are calculated [6, 13, 14, 23, 27, 28].

The methods of Markov's circuits are widely applied to the simulation of concrete problems and are also successfully applied to the reliability analysis [6, 15, 44]. The conditions in the

Markov's circuits are described with transient processes from one condition to the other [15, 23, 27, 28].

With the help of analytical methods, the system is described as a mathematical model. It is important to note that with the analytical methods the reliability factors are calculated on the basis of real processes and accidental system operation. Therefore, the methodology considers the problem as a series of real experiments within a definite time [13]. With the analytical methods, an unchangeable result can be obtained for one and the same system, model and the same data [6, 14, 23, 27, 28].

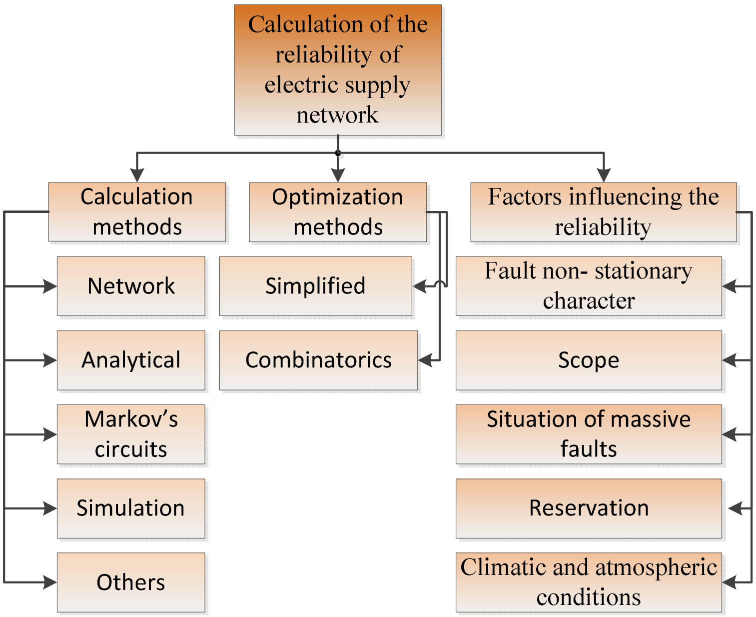


Fig. 1.1. Classification of electric supply reliability calculation methods

By means of simulation methods, an effect of an event on each element is calculated as well as the probability of the event obtaining probabilistic reliability parameters of the expected event. Applying these methods makes it possible to simulate operation of complicated systems and observe in dynamic each possible condition of the system. The basis of the simulation methods is the task to accurately simulate the series of the events according to the accidental principle, obtaining different results for different customers. These events simulated in detail considerably reflect some changes in reliability with small changes in the system [34].

One of the popular simulation methods is Monte Carlo method. With the help of it, the data of elements can be modelled as probabilistic functions. Thus, it makes possible to simulate complex systems, events and calculate different results but not one particular value. Monte Carlo method also makes possible to form rare but important modes of the systems. Each iteration gives a different result; a large number of iterations should be generated where the obtained result varies within a range defined before [7, 13, 34]. If the expected result is an average value than the average value of all the results becomes stable.

Optimisation methods give an opportunity to analyse the solutions of different problems. For example, the number of elements and their localisation are analysed to calculate the effectiveness of capital expenses and find the most optimal sectioning places of the electric supply network [32, 41, 42, 43].

The simplified methods of electric supply network optimisation are used for separate calculations of each network element influence on the electric supply reliability [32].

One of the most applied optimisation strategies is the application of different sectioning elements in accordance with their distance to customers and/or substation, and/or to the nearest element. Combinatorics optimisation methods of electric supply networks are derived from the biologic and cognitive processes — annealing simulations, searching for taboo, genetic algorithm, ant colony optimisation, etc.

When one of the above-mentioned methods is selected, the calculation of electric supply reliability is required taking into account different factors influencing the reliability and their combinations.

After the basic task of reservation, the elements of electric supply can be divided into 3 basic groups — unreserved, reserved and auxiliary. Unreserved elements are those which in case of interruptions cannot be provided with electric supply along the lines or from other sides. Reserved elements are those which in case of interruptions can be supplied from other sides. Auxiliary elements are the elements that in case of interruptions can restore electric supply for the element under consideration, as soon as interrupted element is interrupted [4, 20, 22, 24, 34].

Situation of massive interruptions is formed under particular conditions that result in repeatedly increasing interruption frequency, then the reliability calculations require separate consideration of massive interruptions cases [10].

1.2. Methods for Calculation of the Losses resulting from the Electric Supply Interruptions

The losses resulting from the electric supply interruptions that have economic and social influence on the society can be divided into direct and indirect losses. Direct losses are connected with undelivered electric energy. Indirect losses are not connected with the interruptions themselves but with their consequences. Different types of loss calculations depend on different durations of interruptions, distribution of the customers' groups, methods of result calculations, methods of data obtaining, etc. (Table 1.1.) [16, 26].

Table 1.1

Comparison of the Calculations of Losses Resulting from the Electric Supply Interruptions

Analytical methods	**Simulation methods**	**Methods of customers' interview**
No need to simplify the calculation method	Any phenomenon can be modelled	Objective results require a large number of interviewees
A comparatively short duration of calculations is required	A large duration of searching for the results is required	A high validity of data, long duration of statistical processing are required
The data obtained depend on the accuracy of data	The results depend on the number of iterations	The results depend on the accuracy of the interviewees and level of their response
Obtaining of average values	Results defined in the probabilistic division	The results contain average subjective values

According to the calculation types, the methods of loss calculation can be divided into three subgroups — analytical, simulation and methods of customers' interview [9, 16].

The analytical methods like the calculation of reliability are based on the expenses for electric energy, statistic data of the losses of different customer groups as a result of interruptions, tendencies of the market and opportunities of electric supply reservation for customers. In the use of simulation methods, most of the above-mentioned data are taken into account [11, 24, 25].

With the help of interview methods, the initial data can be obtained by questionnaires, statistics or interview. The evaluations can be compared in accordance with direct or indirect losses and risk of possible interruption [16, 25, 26].

According to the choice of methods described before — analytical, simulation or interview, the direct and indirect losses resulting from interruptions should be analysed and calculated.

The factors influencing the reliability can be divided into subgroups according to the customers of electric energy, undelivered energy or power, duration of interruptions, frequency as well as combining these subgroups in different ways.

The customer groups are divided taking into account equal electric energy consumption and equal interruption losses (Fig. 1.2) [6].

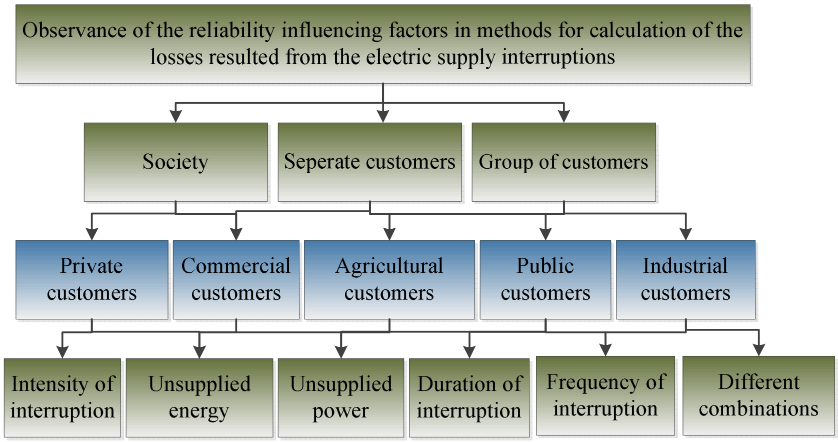


Fig. 1.2. Factors influencing the losses from electric supply interruptions

2. CONDITION OF THE ELECTRIC SUPPLY RELIABILITY AND ITS DEVELOPMENT TENDENCIES IN LATVIA

The electric supply distribution system of JSC Sadales tīkls provides 94 780 km of electric supply network, 132 110/6–20 kV substations, 26 407 transformer substations, ~1.4 million items of overhead line pivots for 1.126 million customer objects. Lithuania and Estonia have relatively fewer territories of forests; therefore, the risks of interruptions because of wind or snow are lower [5]. Lithuania and Estonia have a larger number of 6–35 kV network supply substations that results in shorter average length of the lines till the places of normal distribution. It decreases the number of interrupted customers but increases the expenses of electric network maintenance. It partly explains the fact that in Latvia the duration of interruptions is larger as in the 20 kV network longer sections of lines are interrupted for implementation of the works.

2.1. Reasons and Procedure of the Electric Supply System Interruption Elimination

The interruptions in distribution networks due to natural reasons directly depend on presence/absence of massive interruptions and their number per year as well as the level of the line cleaning per the same time period [1]. Interruptions from birds and animals depend on their migration ways and localisation of the line [1]. Changes in materials during the service life depend on the annual weather conditions, wind and thunderstorm intensity and ambient temperature [2]. In most cases, in Latvia the interruptions of electric supply overhead lines are caused because of the natural conditions. The analysis of the present distribution electric network proves that several factors reduce the quality of electric supply and effectiveness of the enterprise operation: high share of 20 kV overhead lines (79 %), 30–40 % of which are located in forest areas, a large number of non-renewed and physically obsolete lines, insufficient sectioning of the network and absence of a common dispatcher control system, insufficientnumber of 110 kV substations, insufficientvolume of the resources for the planned overview and maintaining of the elements. At the moment, the overview and register of the interruptions of electric supply system is implemented in accordance with the scheme in Fig. 2.1 [33].

The total duration of the electric supply restoration depends on the localisation of interruption and customer within the structure of the network

$$t_r = t_{rep} + t_{rest}, \quad (2.1)$$

where

t_r — total repair duration,

t_{rep} — duration of repair works,

t_{rest} — duration of power supply restoration.

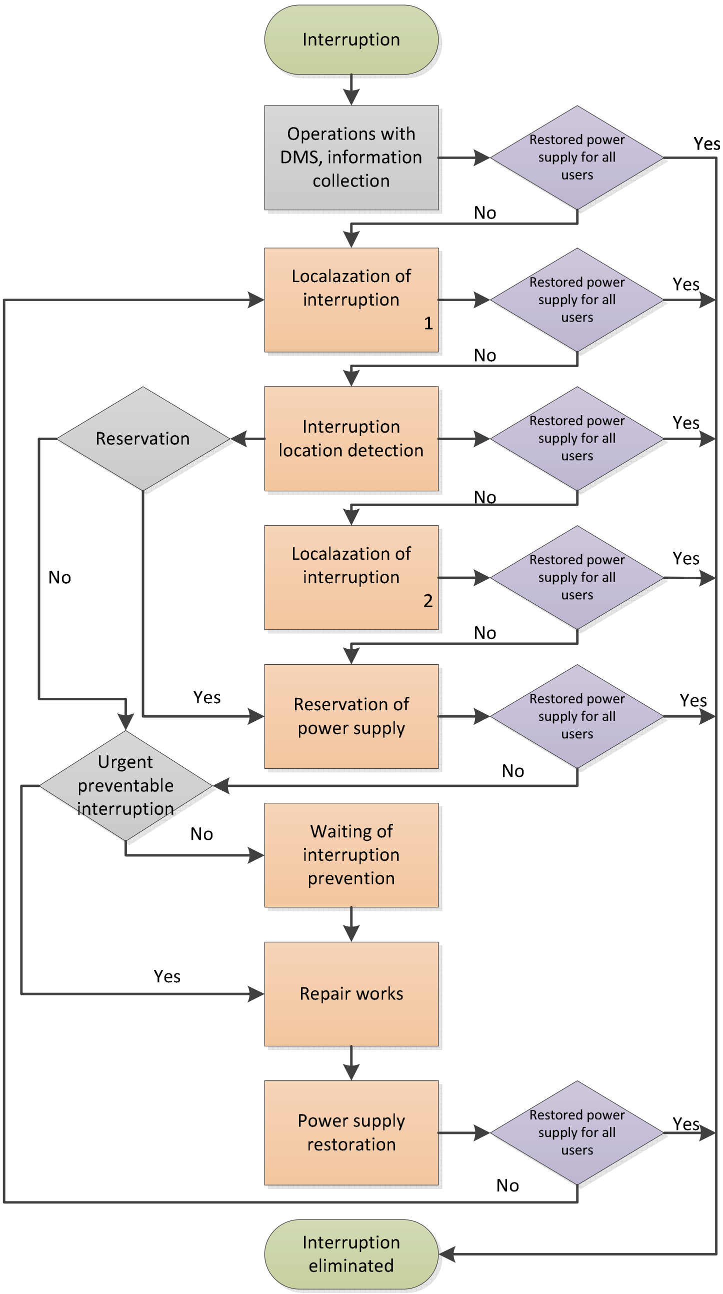


Fig. 2.1. Elimination sequence of interruptions

The total duration of power supply restoration depends on the interruption location, in case of transient interruption it is t_{isol1} in case of permanent interruption, using sectioning it is

$$t_s = t_{isol1} + t_{\det} + t_{rez} + t_{izol2}, \qquad (2.2)$$

where

$t_{isol\,(1,2)}$ — interruption localisation duration,

$t_{\det}$ — duration of interruption location detection,

t_{rez} — reservation duration of power supply,

t_s — switching duration [35].

In case of non-transient interruptions for the customers in the interrupted section of the network, it is equal to the total duration of the interruptions (Fig. 2.2).

$$t = t_s + t_r + t_{wait}\ , \tag{2.3}$$

where

t — total interruption duration,

t_{wait} — start of interruption prevention duration [29, 37, 39].

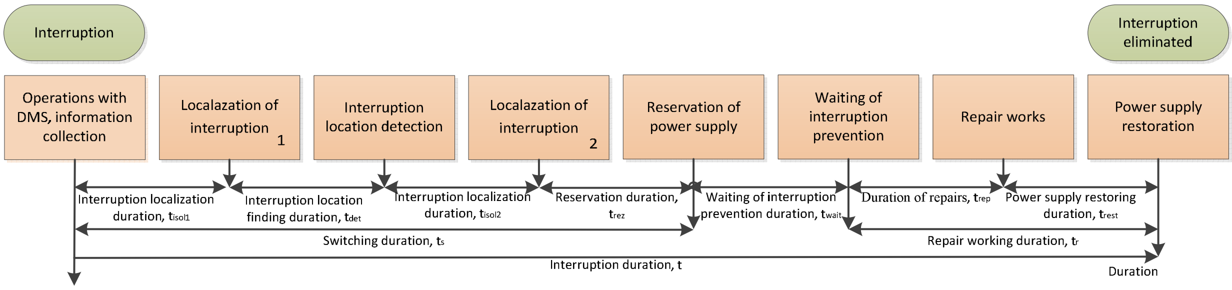


Fig. 2.2. Scale of the duration of electric supply system interruption elimination

2.2. Solutions to the increasing of Electric Supply Reliability

The reliability is effective to increase to such a definite level only after which the further increase has no economic justification [4]. The reducing of interruption frequency in 20 kV distribution networks is possible using insulated or cable lines instead of overhead lines, performing line cleaning, planned replacement of the old elements, preventive service and control of critical elements. The reducing of the interruption duration is possible using interruption place bearers, carrying out optimal reconfiguration of the network after the interruptions, sectioning the distribution network, building additional substations, applying reservation distribution transformers, mobile generators of electric energy, promoting faster work of personnel, ensuring better coordination of the work, implementation of close network, increasing the quantity of sectioning elements, as well as applying smart meters. The goal of JSC Sadales tīkls by the year 2050 is to achieve the following results: not planned (SAIFI) — one interruption per year, planned system average interruption frequency index SAIFI — 0.3 interruptions per year, not planned system average interruption duration index (SAIDI) –40 min per year, planned SAIDI — interruptions duration up to 50 min per year [5].

2.3. Analysis of the Interruptions of Electric Supply Network

During the work the interruptions in 20kV network were investigated without taking into account massive interruptions cases. The author of the Docotroal Thesis not only analysed the interruptions occured during the defined time period, but also the elimination and distribution process of each interruption of the supply system, as well as its duration. Taking into account equal 20 kV load distribution, the network interruptions were analysed in one Latvian region with 711 transformer substations (TS), 1095 km — 20 kV lines, 1688 km — 0.4 kV lines and 14927 customers. In regard to the statistical data of registered operative interruptions, the following information about the interruptions was analysed: the start time of event, the interruption and connection of commutation equipment, sectioning operation, disappearance of voltage, overloading or acute changes in the operation regimes of the elements (load, voltage, temperature, etc.) or an increase in voltage over the admissible level [35, 37]. Then the data were analysed for the duration of the interruption reasons, localisation of the interruptions, and number of interrupted customers. The total duration of each interruption was divided into 6 parts — beginning of the interruption prevention, localisation of the interruption place, detection of the interruption place, reservation, repairs and electric supply restoration, taking into account the number of interrupted customers and transformers, place and reasons of the interruption. Within the interruption, on average about 241.06 customers and 14.35 TS were interrupted. The maximum number of interrupted customers during one interruption was 4725, and maximum number of interrupted TS was 244 (Fig. 2.3). For the interruptions with the registered localisation of the interruption, the average number of customers was 277.09 for one interruption of interrupted supply, and on average there were 16.72 interrupted transformer substations. The duration of localisation was registered for 75.26 % of interruptions. It was connected with the frequency of commutation, operation of relay protection (Fig. 2.4) [37].

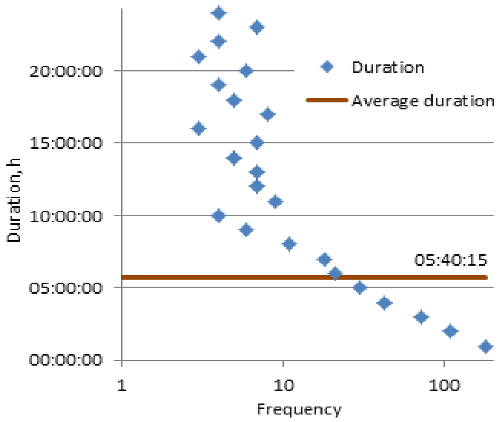


Fig. 2.3. Distribution of interruptions duration

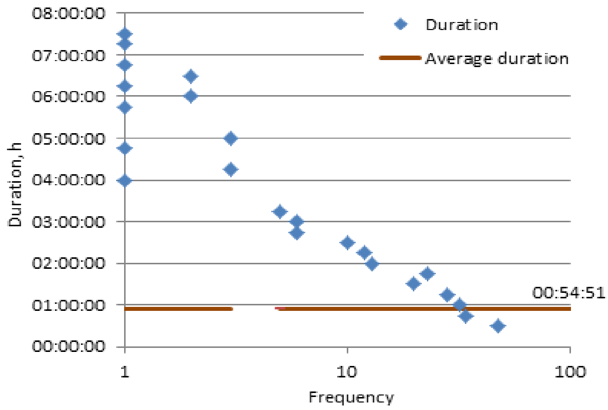


Fig. 2.4. Distribution of localisation duration

For the interruptions with the registered duration of the interruption localisation detection, the average number of customers was 185.35 for one interruption of interrupted supply, and there were on average 12.65 interrupted TS. The duration of interruption localisation detection was registered for 7.85 % of interruptions (Fig. 2.5). For the interruptions with the registered duration of interruption reservation, the average number of customers was 493 for interruption of interrupted supply, and there were on average 27.82 interrupted TS. It was connected with the interruptions place, e.g. the interruption on the main line was signaling about a large number of interrupted customers. The duration of reservation was registered for 24.06 % of interruptions (Fig. 2.6) [37]. It was connected with the interruption place, e.g. the interruption on the main line was signaling about a large number of interrupted customers. The duration of reservation was registered for 24.06 % of interruptions (Fig. 2.6) [37].

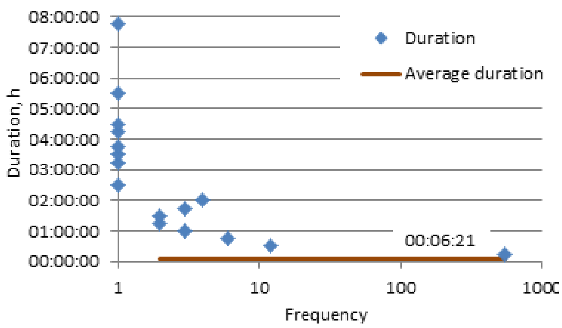


Fig. 2.5. Distribution of detection duration

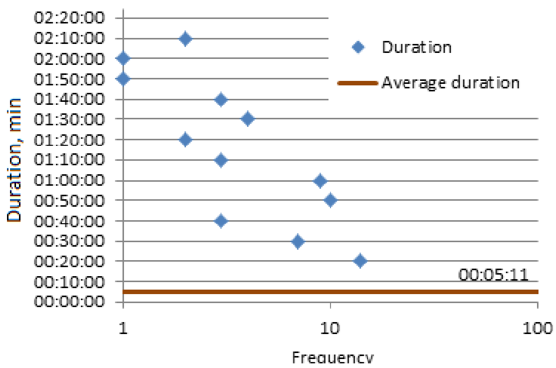


Fig. 2.6. Distribution of reservation duration

For the interruptions with the registered interruption of waiting prevention beginning, the average number of customers was 245.33 for one interruption of interrupted supply, and there were on average 15.75 interrupted TS. The duration of the beginning of interruption prevention was registered for 10.41 % of interruptions, for all of them the interruption took place and/or went on during night hours (Fig. 2.7). For the interruptions with the registered duration of the interruption localisation maintenance, the average number of customers was 207.15 for one interruption of interrupted supply, and there were on average 12.52 interrupted TS. The duration of repairs was registered for 82.08 % of interruptions (Fig. 2.8).

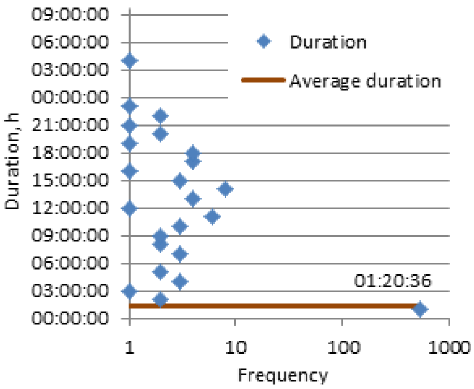


Fig. 2.7. Distribution of waiting of interruption prevention duration

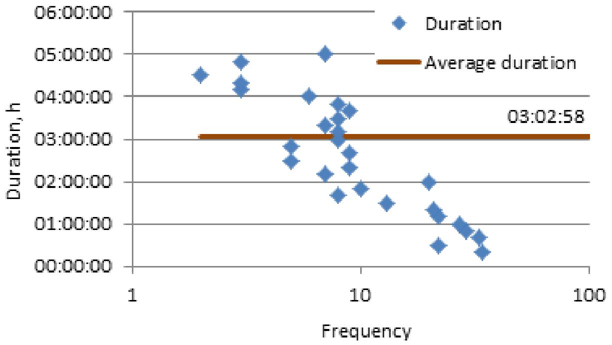


Fig. 2.8. Distribution of repair duration

For the interruptions with the registered duration of the electric supply restoration, the average number of customers was 244.14 for one interruption of interrupted supply, and there were on average 14.89 interrupted TS. The duration of electric supply restoration was registered for 59.22 % of interruptions (Fig. 2.9) [37].

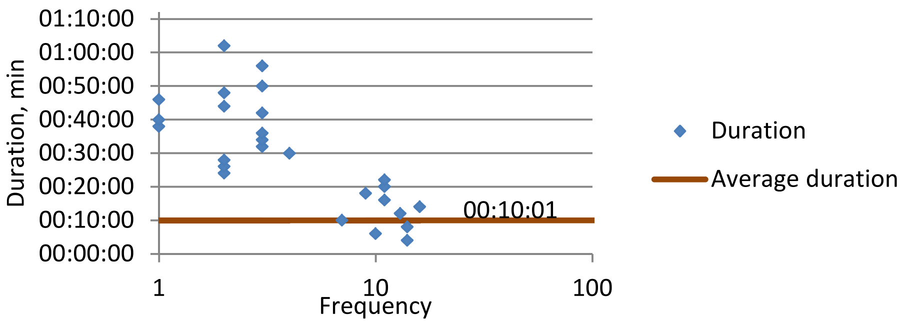


Fig. 2.9. Distribution of power supply restoration duration

Table 2.1

Comparison of the Calculations of Reliability Resulting from the Electric Supply Interruptions

Element/ reliability data	**Statistics on Latvian 20 kV network electric supply reliability**		**Average electric supply reliability data in the European Union**	
	Duration, h	**Frequency, 1/year/pcs. or km**	**Duration, h**	**Frequency, 1/year/pcs or km**
Breakers (per pcs)	3.22	0.0048	4	0.06
Overhead lines (per km)	4.12	0.0935	5	0.065
Power switches (per pcs)	1.74	0.0440	4	0.02
Cable lines (per km)	0.52	0.0217	30	0.019
20/04kV TS (per pcs)	5.19	0.1038	10	0.05

By analysing the interruptions for the period of three years under normal weather conditions and using distribution network (DN) data, the interruption frequency and duration for power switches, overhead lines, cable lines, breakers and 20/0.4 kV TS were calculated. Average parameters of the frequency and duration of interruptions in the world were also used for the comparison purposes (Table 2.1) [37].

2.4. Probation of the Hypothesis of Interruption Duration Probability Distribution

Taking into account the statistic volume of the analysed 20 kV electric supply interruptions, in order to reduce assumptions and obtain precise reliability calculation results, it was necessary to calculate the probability distribution of each interruption. The estimation of the distribution hypothesis was performed in accordance with Hi-quadrant and Kolmogorov–Smirnov distribution functions. The results of Hi-quadrant and Kolmogorov–Smirnov distribution function correspondence were demonstrated in the way of p-values. Usually the higher p-value is, the better distribution function corresponds to the data. For example, if p-value exceeds 0.10, then a zero hypothesis with a level of 0.10 (Table 2.2) is impossible to deny [40].

Table 2.2

Probation of the Hypothesis of Interruption Duration Probability Distribution

	20/04kV TS	**Breakers**	**Power switches**	**Overhead lines**
Total interruption duration	Beta	Exponential	Exponential	Gamma
Waiting of interruption prevention duration				Beta
Repair duration	Weibull	Exponential	Exponential	Weibull
Reservation duration	Weibull	Weibull	Normal	Beta
Interruption location detection duration	Weibull	Exponential		Weibull
Interruption localisation duration	Weibull	Beta	Beta	Exponential
Power supply restoration duration	Weibull	Exponential	Exponential	Weibull

3. METODOLOGY OF CALCULATION OF ELECTRIC SUPPLY RELIABILITY AND LOSSES FROM INTERRUPTIONS

Taking into account a low density of load in the Latvian distribution network, a low loading factor in comparison with other countries of the European Union and a large number of overhead lines, the reliability and losses from interruptions were calculated according to the model of distribution network proposed in the Doctoral Thesis. The values of the electric supply reliability and losses from the interruptions were calculated taking into account the following factors: electric supply network, undelivered electric energy, distribution functions of the interruption duration probabilities, duration of electric supply system interruption elimination for reserved, unreserved and auxiliary elements, as well as the losses of the network, society and customers caused by the interruption [18, 21, 38]. The purpose of the calculations was to consider different scenarios, as well as to calculate the optimisation of the sectioning elements in order to minimise the duration of the interruptions and the losses form the interruptions. To calculate the losses, the following tasks were defined:

a) to model the network and select the criteria for reliability and losses resulting from interruptions;
b) to provide an opportunity to calculate the reliability of electric supply;
c) to provide an opportunity to calculate the losses resulting from the electric supply interruptions;
d) to develop the methods for calculation of the electric supply reliability and losses resulting from the interruptions for different periods of time and models of network taking into account consumption of electric energy, loading factor, length of the line, structure of the network, number of the customers, expenses for the interruption elimination and capital investments, etc.;
e) to develop a method for the calculation of optimal localisation of the sectioning elements with the opportunity to calculate reliability and losses resulting from the interruptions for different modifications of the network models;

f) to calculate the reliability of electric supply and the losses resulting from interruptions and analyse the obtained results.

3.1. Calculation Task of Electric Supply Reliability and Losses resulting from Interruptions

To calculate total losses and reliability of number and localisation of sectioning elements for the analysis of capital investment scenario, the factors influencing reliability considered in the multi-criteria analysis should be taken into account (Fig. 3.1) [8, 18].

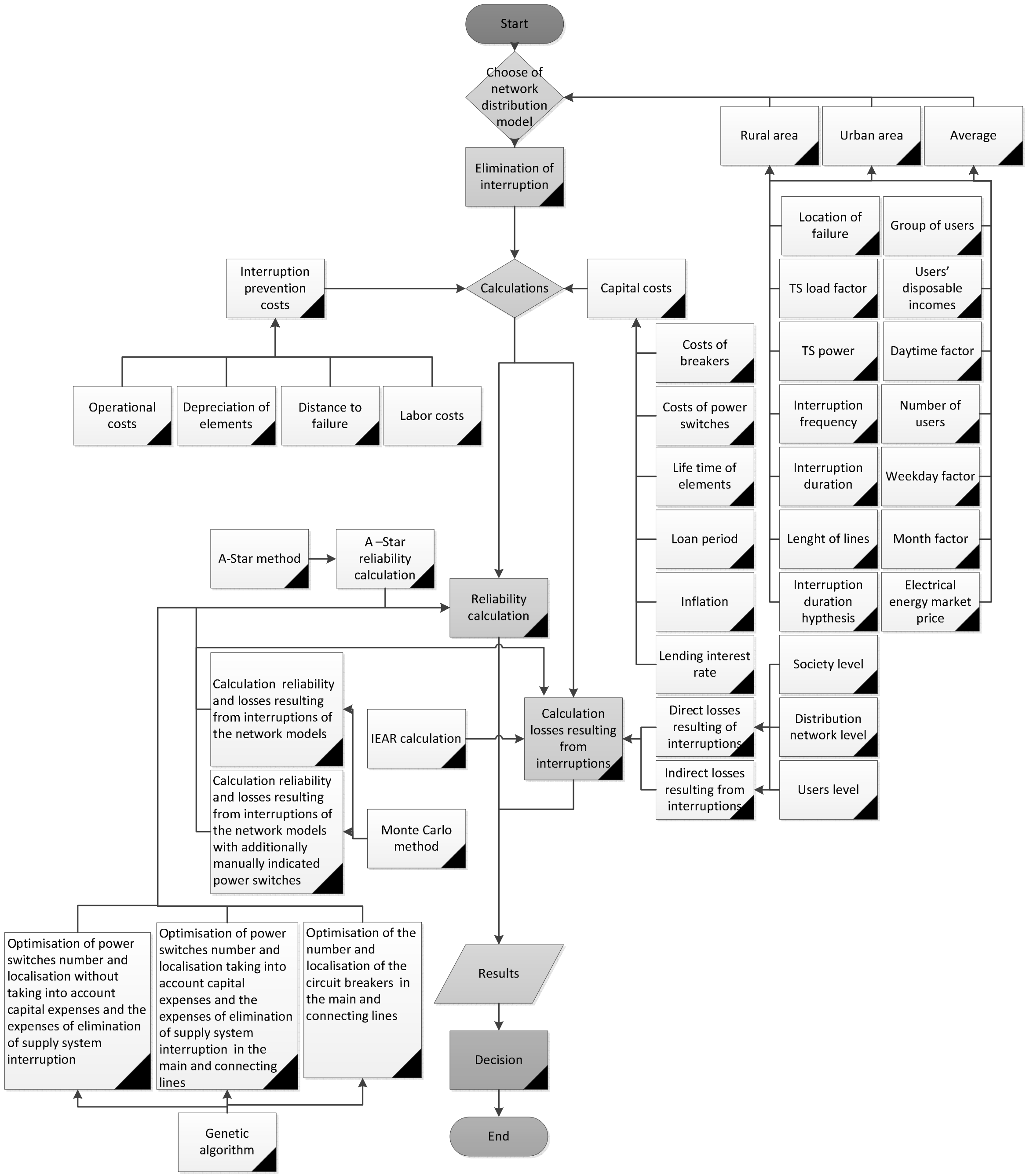


Fig. 3.1. Multi-criteria analysis of calculation of electric supply reliability and losses resulting from interruptions

Taking into account the structure of the present network models and tendencies of the network development, the methods of A–Star, Monte Carlo and genetic algorithm were selected for the calculation of reliability and losses resulting from interruptions; a multi-criteria analysis was applied for the accuracy of the results [30].

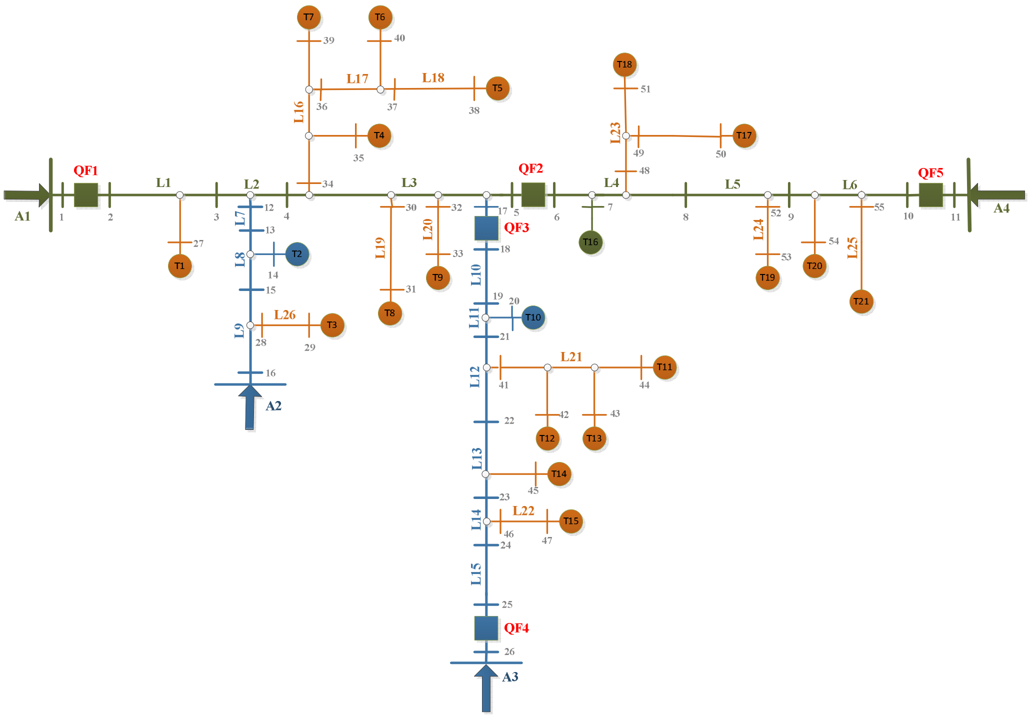
For the optimisation of electric supply network sectioning elements, a genetic algorithm was used in the research.

In accordance with the multi-criteria analysis, the following scenarios were defined:

1) calculation of the losses resulting from the electric supply interruptions;
2) calculation of electric supply reliability by means of A–Star method;
3) calculation of reliability and losses from interruptions by means of Monte Carlo modelling with manual localisation of power switches determined in addition;
4) optimisation of number of power switches and localisation with genetic algorithm (GA) without taking into account capital expenses and the expenses of elimination of supply system interruption;
5) optimisation of number of power switches and localisation on main and connecting lines with GA taking into account capital expenses and the expenses of elimination of supply system interruption;
6) optimisation of number of breakers and localisation on main and connecting lines with GA taking into account capital expenses and the expenses of elimination of supply system interruption.

3.2. Selection of Model of Electric Supply Network

DN 20 kV network was analysed in detail and calculated. It resulted in the developed model of network (Fig. 3.2).



main line, connecting lines, branch line, A — supply source, A1, A4 — supply source of main line, A2, A3 — supply source of connecting lines, L1–L26 — lines, QF1 –QF5 — power switch, T1–T21 — transformer substations, T16 — transformer substation connected to the main line, T2, T10 — transformer substation connected to a connecting line, 1, 2, 3,…, 55 — breakers, QF4, QF5, 16 — places of distribution

Fig. 3.2. 20 kV Model of 20 kV distribution system

The reservation of electric supply is possible along the connecting line for supply sources A2, A3 and A4. In normal regime, the power switches QF1, QF5, QF3 are in "*on*" condition. In normal regime, power switches QF4 and QF2 are in "*off*" condition. Points 16, QF4 and QF5 are distribution places.

Summarising the information about the Latvian distribution networks in different regions and territories with different population density, different incomes and other parameters, the models of three types for the electric supply network models were developed: urban, rural areas and average according to the statistical calculations of probabilistic distribution of data. The analysis of the elimination of interruptions of electric supply system and the determination of duration of each customer interruption were performed in accordance with Fig. 2.1. For the calculations of the losses of customers caused by the interruptions, the customers group was selected according to TS location in the network, TS power, loading factor and structure of the network. For the simplification of calculations and calculation of the losses caused by the interruptions to each group of customers, the same types of customer groups were assumed to be connected to one TS. The calculations also assumed that the average number of the customers connected to TS was 40, in a rural area — 20 and in an urban area — 60. The length of the overhead lines was selected in accordance with the results of the line thorough analysis and relations of these lines. Taking into account DN data in the Latvian territory and, correspondingly, in urban and rural areas, the total average length of the lines in Latvia was assumed to be 35 km, for a rural area — 50 km and in cities — 20 km. The ratio of main lines, connecting lines and branch length to the average model of electric supply network was 1 – 2 – 1, for the model of rural area it was 1 – 2 – 2 and for the model of urban area — 1 – 2 – 2.

3.3. Selection of Calculation Methods for Electric Supply Reliability and Losses from Interruptions

Taking into account the structure of the present network and tendencies of the network development, the methods of interrupted energy assessment rate (IEAR), Monte Carlo and genetic algorithm were selected for the calculation of reliability and losses resulting from interruptions, as well as the multi-criteria analysis was applied for the accuracy of the results [8, 30].

While the process of algorithm development, a structure was developed taking into account all the restrictions. The selected method unites several algorithms into one set. The time of calculation in this algorithm is acceptable and its structure does not require to be modified if the initial data of the network are not changed. The proposed algorithm allows comparing the number of some power switches and breakers, and localising them in the network models. The method of reliability calculation does not take into account a possibility of massive interruptions. The method assumes that all elements in relation to concrete transformer substations are divided into reserve, unreserved and auxiliary elements [8].

In the analysis of reservation possibilities, different solutions to the formation of capital investments were compared. The the result of this, a method with an opportunity to change the structure and reservation abilities of the network was created, thereby improving the accuracy of the results and providing possibility to consider different development solutions. In a general case for a particular group of customers, the losses resulting from the interruptions depend on the number of customers(N), the month $f_m(t)$, the day of a week $f_n(t)$, and time of a day $f_h(t)$. Thus, the average income of the correspondent customers is $C(d)$ (€/year) and t_d. — duration of interruptions, h [6].

$$ECOST\,(t,N,d) = N \cdot f_m(t) \cdot f_n\,(t) \cdot f_h\,(t) \cdot C(d) \cdot t_d\,. \tag{3.1}$$

The present income of the customers $C(d)$ can be calculated taking into account the regularity of income, expenses and profit

$$C_i(d) = \frac{\sum_{i=1}^{n} \left[S_i \cdot \left(1 + r_i\right) - E_{ai}\right]}{12}, \tag{3.2}$$

where

S_i — annual primary expenses (e.g., materials, logistics expenses, utilities, rent expenses, taxes),

r_i — annual profit,

E_{ai} — other expenses depending on the electric energy consumption (for example, salaries of the staff, penalties, over-planning) [36].

Therefore, according to [39] $C_i(d)$ can be expressed as

$$C_i(d) = P_i, \text{ €/year}, \tag{3.3}$$

where

P_i — annual present income of the customers.

Annual profit of the customers is

$$I_i = P_i - E_i, \tag{3.4}$$

where

I_i — annual profit of the customers,

E_i — annual expenses of the customers [29].

Taking into account the information sources [6, 19], the month, week and day–night time factors were assumed to be applicable to the customers of electric energy in Latvia.

For the determining of the efficiency of the planned capital investments in the network with several possible solutions that can change the model of the network, the economic calculations were required. Using in the multi-criteria analysis used factors, factors are changed to single function, taking into an account capital investments, interruption elimination expenses, irect and indirect losses of the customers, number of new elements, number of customers. The expenses are formed from

$$C = \sum_{i=1}^{n} C_{ki} + \sum_{i=1}^{m} C_{EUi} + C_{AN} \rightarrow \min \tag{3.5}$$

where

C — losses from interruptions during the calculation period, €/year,

C_{ki} — capital investment expenses, €/year,

C_{ANi} — interruption elimination expenses, €/year,

C_{EUi} — direct and indirect losses of the customers, €/year,

n — number of new elements,

m — number of customers [4].

The capital investments for a time period are calculated on the basis of NPV method:

$$C_{ki} = \frac{C_0 (1+\frac{int_r}{100})^{t_{cr}}}{(1+\frac{inf}{100})^{t_{cr} * t_{ei}}}, \tag{3.6}$$

where

C_0 — expenses of element construction, €,

int_r — loan rate ,%,

t_{cr} — loan period, years,

inf — inflation, %,

t_{ei} — duration of element service life, years.

In accordance with the survey results of producers, building and engineering enterprises, the calculations demonstrated that the expenses for an air power switch with protection in a rural area were 30,000 EUR, in an urban region, in its turn, to build a compact transformer substation the expenses were 50,000 EUR. The average expenses for one power switch were assumed to be 40,000 EUR and those for a breaker — 5,000 EUR. A linear method was acceptable for the purchased elements with an annual decommission norm of 4 %. The annual expenses for the elimination of electric supply system interruptions were assumed to be 2 %, and the annual level of inflation — 3 %. In accordance with the European Central Bank recommendations, the rate of credit enterprises is 7 %. The credit time periods are 10 and 25 years. In the multi-criteria analysis, the losses resulting from the electric supply interruptions were eliminated within all three levels. The consumption and duration of the interruptions were analysed for the calculation of undelivered electric energy volume. The losses resulting from the interruption of energy supply were calculated according to the market average prices.

3.4. Description of Calculation of Electric Supply Reliability and Losses from Interruptions

According to [36, 37], the comparison of the statistical data of several states requires making IEAR calculation for all groups of customers, average, rural areas and cities within day–night, month, day of a week for the average income of the customers. For the analysis and comparison of the obtained data and comparison with the IEAR of other countries, the maximum and minimum IEAR values were required to be calculated. Taking into account the present statistical data, the average losses resulting from the electric supply interruptions should be calculated by means of the IEAR method [37].

A–Star algorithm is a heuristic method for the way search in a given graph. The algorithm detects whether there is a way from the starting point to the end point. There are also algorithm modifications, which are intended for checking whether the customer is connected to a power source. In the algorithm modifications, additional restrictions are taken into account — the reserve source searching in case of network element interruption in accordance with network node positions.

A–Star is a method that follows a reservation principle. Its basis is the dependence of possible interruption duration on the interrupted element in relation to the customers or the point under consideration, if the interruption takes place in an element of the network without an opportunity to reservation, or with such an opportunity, or it is connected to branches (see Chapter 4). The total frequency of the interruptions in the elements of 20 kV electric supply network is formed from 3 groups of elements — reserve, unreserved and auxiliary [20, 39]. The localisation of each customer in the network is unique. If to take into account the features of the network structure according to a particular customer, it is possible to obtain a more accurate duration of the interruptions and frequency for each customer. Basic difficulties in the calculations are related to the determination of the supply paths and distribution of the correspondent elements. The method of A–Star is acceptable to apply for simplification of these calculations (see Chapter 4). In any TS, the elements of electric supply circuit can be divided into three basic groups: unreserved, reserved and auxiliary [46]. In case of interruption, unreserved elements require repairing and/or changing. For the reserved elements, the duration of the considered interruptions is determined with the duration of supply interruption to the reservation circuits. In case of interruptions, the auxiliary elements can be interrupted from the considered TS supply circuit and at once restore the supply. The auxiliary elements do not have a basic task of reservation. The frequency of the element interruptions regarding the considered TS can be found as follows:

$$\begin{cases} \omega N[x] = \omega_{TA}[x] + \omega N_{lin}[x] + \omega N_{AT}[x] + \omega N_{JS}[x], \\ \omega R[x] = \omega R_{lin}[x] + \omega R_{AT}[x] + \omega R_{JS}[x], \\ \omega P[x] = +\omega P_{lin}[x] + \omega P_{AT}[x] + \omega P_{JS}[x], \end{cases} \quad (3.7)$$

where

$\omega N[x]$ — frequency of failures of unreserved elements;

$\omega_{TA}[x]$ — frequency of failures of unreserved TS;

$\omega N_{lin}[x]$ — frequency of failures of unreserved lines;

$\omega N_{AT}[x]$ — frequency of failures of unreserved breakers;

$\omega N_{JS}[x]$ — frequency of failures of unreserved power switches;

$\omega R[x]$ — frequency of failures of reserved elements;

$\omega R_{lin}[x]$ — frequency of failures of reserved lines;

$\omega R_{AT}[x]$ — frequency of failures of reserved breakers;

$\omega R_{JS}[x]$ — frequency of failures of reserved power switches;

$\omega P[x]$ — frequency of failures of auxiliary elements;

$\omega P_{lin}[x]$ — frequency of failures of auxiliary lines;

$\omega P_{AT}[x]$ — frequency of failures of auxiliary breakers;

$\omega P_{JS}[x]$ — frequency of failures of auxiliary power switches.

The total frequency of failures of the element interruptions was calculated with the formula:

$$\omega[x] = \omega N[x] + \omega R[x] + \omega P[x]. \qquad (3.8)$$

The total frequency of the element interruptions $a[x]$ can be calculated as follows:

$$a[x] = aN[x] + aR[x] + aP[x], \qquad (3.9)$$

where

$aN[x]$ — number of unreserved elements;

$aR[x]$ — number of reserved elements;

$aP[x]$ — number of auxiliary elements.

The total duration of the element interruptions $\tau[x]$ was calculated as follows:

$$\tau[x] = aN[x] \cdot tN + aR[x] \cdot tR + aP[x] \cdot tP, \qquad (3.10)$$

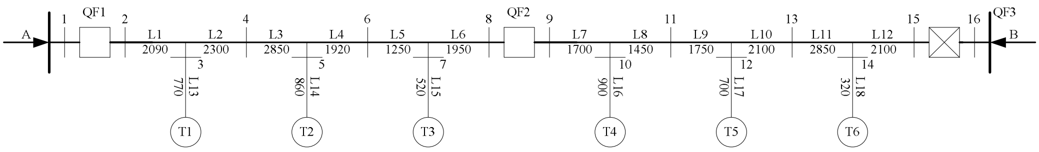
where

tN — duration of interruption of unreserved elements;

tR — duration of interruption of reserved elements;

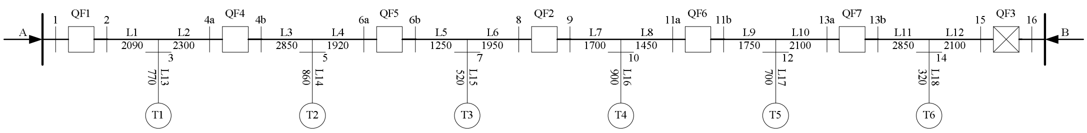
tP — duration of interruption of auxiliary elements.

This principle is applied to A–Star method. With the help of A–Star method, electric supply models of two types were analysed — the model of the first type (Fig. 3.3) and that of the second type (Fig. 3.4) with additionally determined localisations of power switches.



A, B — supply sources, QF — power switch, L1 – L18 — lines, 1– 14 — breakers

Fig. 3.3. A — Star and electric supply model of the first type applied to the analytic calculation of reliability



A, B — supply sources, QF — power switch, L1 – L18 — lines, 1– 14 –breakers

Fig. 3.4. A–Star and electric supply model of the second type applied to the analytic calculation of reliability

These two models of electric supply systems were selected for calculation of efficiency of the number and localisation of auxiliary power switches. In the calculation, the parameters of the element reliability were accepted in accordance with Table 2.2 — statistical data of electric supply reliability of 20 kV network in Latvia (Table 2.1), and the length of the modelled lines was selected in relation to an average length of the lines in Latvia.

The electric supply reliability and the losses resulting from the electric supply interruption for the models of Fig. 3.2 with additional manually indicated localisation of power switches were calculated on the basis of Monte Carlo modelling method. The calculation took into account the analysis of the factors influencing the reliability for the urban and rural areas of electric supply network models as well as for the average model with the purpose to calculate the expected duration of the interruptions without the analysis of previous localisation of power switches [7, 30, 38].

Genetic algorithm is a heuristic optimisation method, which simulates the natural evolution of the phenomenon and leaves only those options that are best suited for the environment and the posed requirements. The algorithm does not try to optimise only one solution group. Each solution is a coded value in series with a number of unique variables. These variables are the location of power switches and / or breakers in network models. In this way, the algorithm is looking for the optimal network configuration. Calculation of reliability and losses from interruptions for number and placement of additionally installed power switches and breakers in network models was carried out to determine the optimal number and location of power switches and breakers, minimising the interruption duration and losses from interruptions.

The reliability and the losses from interruptions were calculated according to the number and localisation of the additional power switches and breakers in the network to define the optimal number and localisation of the power switches and breakers, minimising the duration of interruptions and losses resulting from the interruptions. The optimisation of the number and localisation of the power switches and breakers was performed with the help of GA, taking into account the data of the electric supply network model, undelivered electric energy, functions of probabilistic distributions of the interruption duration, duration of the interruption elimination for reserved, unreserved and auxiliary elements and losses of the network, society and customers, but not taking into account the capital investments for power switches [18, 21, 38]. The calculation of the reliability and losses from interruptions, according to the number and localisation of additionally placed power switches in main lines and connection lines, was performed with the aim to define an optimal number and localisation of power switches taking into account the capital investments for power switches [21]. The calculation of reliability and losses made by means of GA, according to the number and localisation of additionally placed breakers in main lines and connecting lines, taking into account the expenses for the capital investments and elimination of interruptions of the electric supply system gives an opportunity to select the number and localisation of the breakers minimising the losses of distribution networks, society and customers resulted from the interruptions as well as minimising the duration of the interruptions [21].

4. CALCULATION OF ELECTRIC SUPPLY RELIABILITY AND LOSSES RESULTING FROM INTERRUPTIONS

The computer model consists of the following basic elements: module of data base, module for the calculation of reliability and losses.

The calculation methodology of electric supply reliability and losses resulting from interruptions was performed:

a) a mathematical model of the electric supply network oriented to the calculation of electric supply reliability and losses resulting from the interruptions was developed;
b) a structure of a data base storing the data about the statistic model was developed;
c) a coding principle of the model dynamic structure was developed;
d) a computer model operating in accordance with the algorithm in Fig. 3.1 and modelling the interruptions and reply to them in respect to the statistic and dynamic structure of the model, i.e. initial localisation of the interruption, detection, reservation, accurate

localisation, elimination of the interruption, repair and electric supply restoration, was developed;

e) one modelling resulted in the obtaining of total duration of the interruptions, total electric energy undelivered to each customer and total losses from interruptions of each customer;

f) one model was implemented several times for the statistic results to reduce the stochastic effect.

4.2. Results of IEAR Calculation

In accordance with the information sources [36, 37], the statistical data of several countries were compared, the calculated interrupted energy assessment rate (IEAR) was determined for all groups of customers, the values of maximum and minimum undelivered electric energy were calculated [37].

IEAR calculated for an average electric supply network model is demonstrated in Fig. 4.1. IEAR calculated for an electric supply network model in rural areas is demonstrated in Fig. 4.2. IEAR calculated for an urban electric supply network model is demonstrated in Fig. 4.3. The summarised data of Fig. 4.1. show that the losses from the interruptions in 20 kV electric supply network in Latvia are equivalent to those in Finland, Norway, the Netherlands, USA and Sweden (Table 4.1) [6, 13, 37].

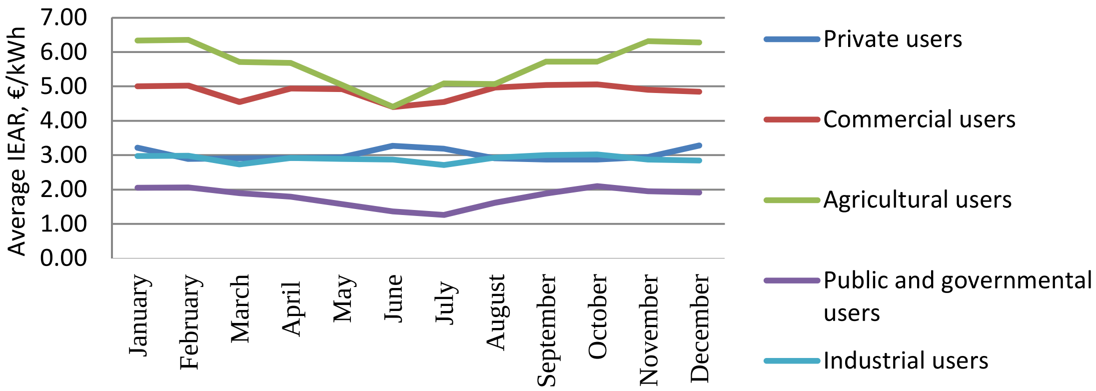


Fig. 4.1. Average IEAR

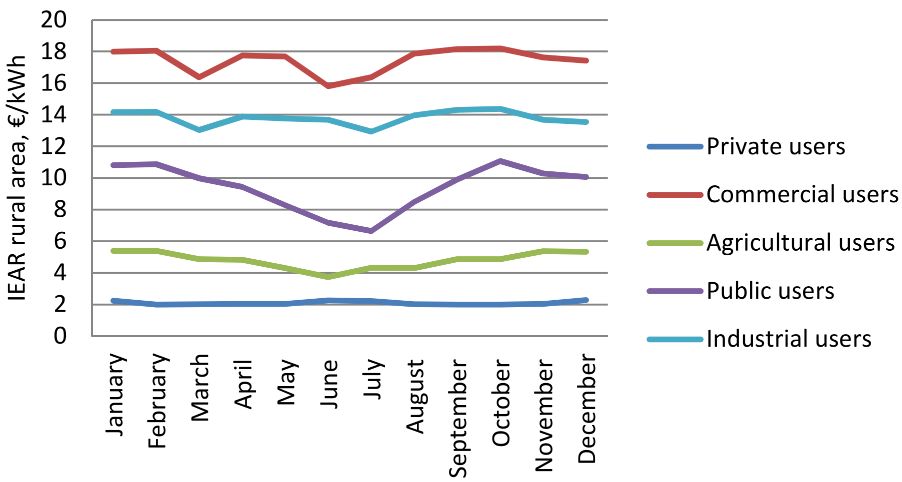


Fig. 4.2. IEAR in a rural area

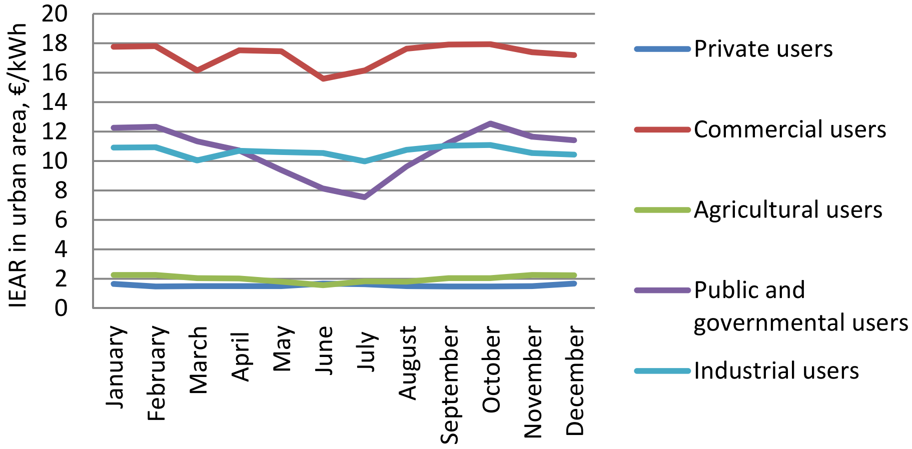


Fig. 4.3. IEAR in an urban area

Table 4.1

Losses Resulting from the Electric Supply Interruptions, €/kWh

Type of customers/ Country	Finland	Norway	The Netherlands	The USA	Sweden	Latvia	Average in Latvia
Private customers	2–7	0.98	16.4	7–10	2–5	0.77–5.22	2.22
Agricultural customers	3–13	1.83	3.9	15	3–10	0.68–7.58	3.53
Commercial customers	2–47	12.07	7.9	60	5–124	1.82–25.92	12.67
Public and government customers	5–41	1.59	33.5	80	3–30	0.31–19.07	6.85
Industrial customers	4–20	1.59–8.05	0.3–33.1	17–56	10–47	0.89–19.63	6.85

4.3. Results of the Reliability Calculations obtained with the Use of A–Star Method

For the assessment of the results, the calculations were made by means of A–Star method, where unreserved, reserved and auxiliary elements were calculated with the developed computer program; the calculations were made analytically by means of Excel software for comparison and estimation of the result accuracy. As a result of experiment, the reliability of electric supply was calculated by means of A–Star method and analytically. The obtained results are provided in Table 4.2.

Table 4.2

Losses Resulting from the Electric Supply Interruptions, €/kWh

	TS	Analytical calculation		A–Star calculation	
		SAIFI	SAIDI	SAIFI	SAIDI
		1/year	min/year	1/year	min/year
First type model of electric supply	T1	2.78	210.76	2.82	211.55
	T2	2.78	211.45	2.80	209.73
	T3	2.78	208.83	2.79	207.23
	T4	2.78	211.76	2.81	209.65
	T5	2.78	210.22	2.83	208.39
	T6	2.78	207.29	2.84	205.60
Second type model of electric supply	T1	2.80	214.47	2.81	214.47
	T2	2.80	215.16	2.82	215.16
	T3	2.80	212.54	2.80	212.54
	T4	2.80	215.47	2.80	215.47
	T5	2.80	213.93	2.79	213.93
	T6	2.80	211.00	2.78	211.00

A–Star method gives an opportunity to calculate small electric supply networks where the localisation of sectioning elements can be manually indicated increasing thus the number of the calculations necessary for the determination of optimal number and localisation of sectioning elements. The advantage of the method is a short duration of the calculations [39].

4.4. Calculation Results of Reliability and Losses from Interruptions by Monte Carlo Method

The purpose was to calculate the parameters of reliability and losses resulting from the interruptions. Application of Monte Carlo method gives an opportunity to obtained more accurate results using distribution of probabilities and reducing the number of assumptions. Results of the calculations by means of Monte Carlo method are reflected in Table 4.3 and Fig. 4.4.

Table 4.3

Calculation Results of the Electric Supply Reliability and Losses from Interruptions

	Model		
	average	**rural**	**urban**
Expected undelivered electric energy, kWh/TS	2933.39	1432.96	5976.87
Losses of DN resulting from interruption, €/TS	495.74	242.17	1010.09
Losses of customers resulting from interruption, €/TS	948.10	931.03	2732.87
Losses of society resulting from interruption, €/TS	87.44	87.79	62.92
Frequency of interruptions in overhead lines per km	1.84	3.07	1.70
Frequency of interruptions of power switches for 1 item	0.03	0.04	0.08
Frequency of interruptions of 20/0.4 kV TS for 1 item	0.22	0.21	0.24
Frequency of interruptions of breakers for 1 item	0.62	0.46	0.54
SAIFI, 1/year	2.71	3.78	2.57
SAIDI, min/year	189.67	265.11	152.11
IEAR, €/kWh	10.96	18.48	13.37
Total losses resulting from interruptions, € per year/TS	**1531.28**	**1260.99**	**3805.89**

The results obtained from the calculations with the localisation of manually indicated power switches, i.e., with one, two or three power switches, are shown in Tables 4.4–4.6.

Table 4.4

Results of the Network Model Calculation with One Additional Manually Indicated Power Switch

	Model		
	average	**rural**	**urban**
Expected undelivered electric energy, kWh/TS	2572.63	1442.81	5824.31
Losses of DN resulting from interruption, €/TS	434.77	243.83	984.31
Losses of customers resulting from interruption, €/TS	791.63	905.26	2024.16
Losses of society resulting from interruption, €/TS	87.79	91.26	69.12
Frequency of interruptions in overhead lines per km	1.95	3.20	1.64
Frequency of interruptions of power switches for 1 item	0.04	0.07	0.06
Frequency of interruptions of 20/0.4 kV TS for 1 item	0.24	0.20	0.21
Frequency of interruptions of breakers for 1 item	0.58	0.75	0.71
SAIFI, 1/year	2.81	4.21	2.62
SAIDI, min/year	175.33	114.89	159.33
IEAR, €/kWh	10.73	18.05	11.10
Total losses resulting from interruptions, € per year/TS	**1314.19**	**1240.36**	**3077.59**

For an average electric supply model in 20 kV distribution network with one additional manually indicated power switch, the total losses resulting from the interruptions are reduced by 14 %, for the models of rural areas — by 1.6 %, for the models of urban areas — by 19 %.

Table 4.5

Results of the Network Model Calculation with two Additional Manually Indicated Power Switches

	Model		
	average	**rural**	**urban**
Expected undelivered electric energy, kWh/TS	2471.99	1452.65	6025.36
Losses of DN resulting from interruption, €/TS	417.77	245.50	1018.29
Losses of customers resulting from interruption, €/TS	734.05	879.50	1992.90
Losses of society resulting from interruption, €/TS	86.62	94.72	70.36
Frequency of interruptions in overhead lines per km	1.72	3.31	1.78
Frequency of interruptions of power switches for 1 item	0.01	0.02	0.05
Frequency of interruptions of 20/0.4 kV TS for 1 item	0.22	0.24	0.25
Frequency of interruptions of breakers for 1 item	0.72	0.70	0.80
SAIFI, 1/year	2.66	4.28	2.88
SAIDI, min/year	166.78	280.11	164.33
IEAR, €/kWh	10.52	17.63	10.74
Total losses resulting from interruptions, € per year/TS	**1238.44**	**1219.73**	**3081.55**

For an average electric supply model in 20 kV distribution network with two additional manually indicated power switches, the total losses resulting from the interruptions are reduced by 19 %, for the models of rural areas — by 3.2 %, for the models of urban areas — by 19 %. For an average electric supply model in 20 kV distribution network with three additional manually indicated power switches, the total losses resulting from the interruptions are reduced by 22 %, for the models of rural areas — by 21 %, for the models of urban areas — by 22.8 %.

Table 4.6

Results of the Network Model Calculation with three Additional Manually Indicated Power Switches

	Model		
	average	**rural**	**urban**
Expected undelivered electric energy, kWh/TS	2420.42	1195.60	5410.89
Losses of DN resulting from interruption, €/TS	409.05	202.06	914.44
Losses of customers resulting from interruption, €/TS	700.20	712.95	1961.65
Losses of society resulting from interruption, €/TS	78.60	80.31	61.88
Frequency of interruptions in overhead lines per km	1.83	3.22	1.74
Frequency of interruptions of power switches for 1 item	0.08	0.04	0.05
Frequency of interruptions of 20/0.4 kV TS for 1 item	0.20	0.24	0.28
Frequency of interruptions of breakers for 1 item	1.28	0.70	1.04
SAIFI, 1/year	3.39	4.19	3.11
SAIDI, min/year	164.78	231.11	145.44
IEAR, €/kWh	10.31	17.48	11.40
Total losses resulting from interruptions, € per year/TS	**1187.85**	**995.32**	**2937.97**

As it is obvious from Tables 4.4–4.6 and Fig. 4.4, the optimal localisation of the power switches in the network is a significant factor for improving of electric supply reliability and, therefore, decreasing of the losses from interruptions. The absence of the optimal localisation of sectioning elements in the network can cause an increase or insignificant decrease in the losses resulting from the interruptions as well as the manually indicated localisation of the sectioning elements does not give an opportunity to calculate the efficiency of capital investments for increasing the reliability level [38].

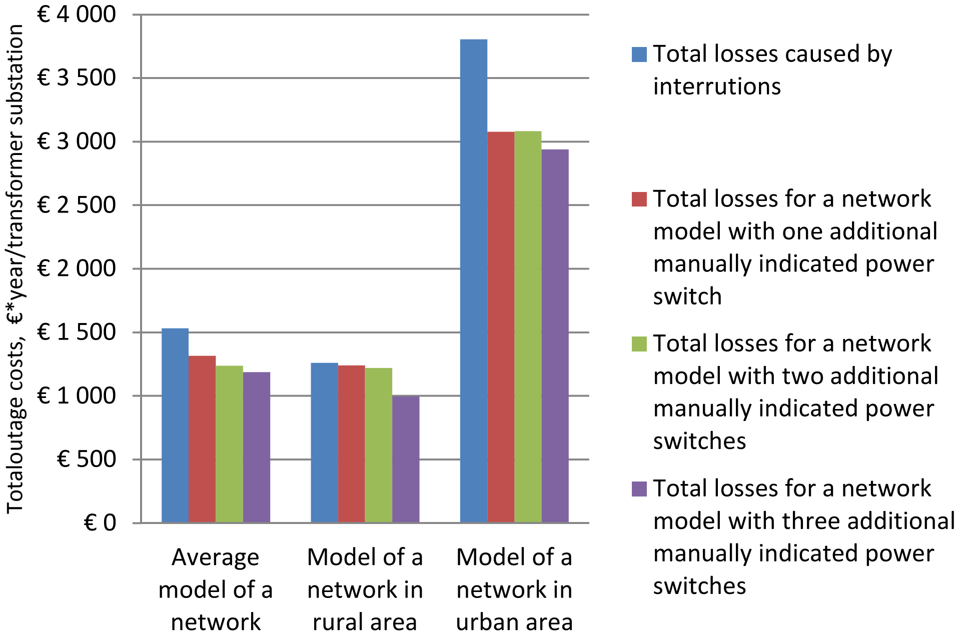


Fig. 4.4. The total losses resulting from interruptions

The reducing of the losses from interruptions is directly proportional to TS power, number of customers, consumption of electric energy and income of the customers.

It can be explained by the differences in the loss decreasing. The advantage of the method is the speed of calculations and variety of the obtained data [7, 30].

5. THE OPTIMISATION OF ELECTRIC SUPPLY NETWORK FROM THE RELIABILITY POINT OF VIEW

The optimisation of the reliability of electric supply and losses resulting from interruptions in the sections was performed in accordance with the approaches mentioned in Chapter 4 and additionally based on the factors minimising losses from interruptions and maximising reliability, optimal structural region of the network searched with GA, electric supply network models of average, rural and urban areas , adding power switches and breakers in the lines. The number and localisation of the power switches and breakers were optimised with the help of GA. The structure of the network model was fulfilled with a module of genetic algorithm for the optimal network configuration. For the investigation of the influence of the number and localisation of power switches and breakers on the losses from interruptions, the interruptions of TS were modelled as it increased the losses for the customers connected to this point [18, 38]. The number and localisation of power switches were optimised according to the principles of multi-criteria analysis applied to the previous algorithms, accelerating in addition the speed of calculation, using the factors of expenses for the elimination of electric supply system interruption. In this process, the elimination of the electric supply system and capital investments were taken into account for the electric supply models of average, rural and urban areas with the loan periods of 10 years, 20 years and without loan. The calculation of the reliability and losses from interruptions according to the number and localisation of additionally placed power switches in main lines and connection lines was performed with the aim to calculate an optimal number and localisation of power switches minimising the duration of the interruption and losses resulting from these interruptions [21]. The calculation of reliability and losses, made by means of GA according to the number and localisation of additionally placed power switches in main lines and connecting lines, taking into account the expenses of the capital investments and elimination of interruptions of the electric supply system, gives an opportunity to select the number and localisation of the power switches, minimising the losses of distribution networks, losses of the society and customers resulting from the interruptions as well as minimising the duration of the interruptions decreasing the time of the calculations.

The calculation of reliability and losses, made by means of GA according to the number and localisation of additionally placed breakers in main lines and connecting lines, taking into account the expenses of the capital investments and elimination of interruptions of the electric supply system, gives an opportunity to select the number and localisation of the breakers, minimising the losses of distribution networks, society and customers resulting from the interruptions as well as minimising the duration of the interruptions [21].

5.1. Results of Optimisation of Power Switch Number and Localisation without taking into Account Capital Expenses and the Expenses of Elimination of Supply System Interruption

The optimisation of power switches for all models of electric supply networks without taking into account the capital investments and the expenses of interruption elimination was performed with the purpose to estimate the influence of the power switches on the reliability of electric supply and losses resulting from the interruptions.

With the minimised total duration of electric supply interruptions and losses for the network, society and customers resulting from the interruptions without taking into account capital investments, the minimum number of power switches for an average network model was 18 items, for the network model of urban area — 15 items. It was connected with a shorter length of the line, higher TS loading factor, larger number of customers and higher annual consumption of electric energy. For the network model of rural area with the minimised total duration of electric supply interruptions and losses for the network, society and customers resulting from the interruptions without taking into account capital investments, the minimum number of power switches was 18 items. It was connected with a longer length of the line, lower TS loading factor, smaller number of customers and lower annual consumption of electric energy.

Taking into account the structure of the network model, we could conclude that the localisation of power switches was mostly on main lines and connecting lines and at industrial, public and governmental, and commercial customers connected to TS, and less often private customers. Localisation of power switches on the branch lines did not fully give an idea about an optimal number of power switches. Therefore, the optimisation of the sectioning elements in the further algorithms was assumed to be performed for main and connection lines only. To obtain more accurate results, the optimisation of number and localisation of the power switches required to take into account the expenses for interruption elimination and capital investments [38].

5.2. Results of Optimisation of Power Switch Number and Localisation taking into Account Capital Expenses and the Expenses of Elimination of Supply System Interruption

The decision to optimise the power switches, taking into account the capital investments and expenses for interruption elimination, was made on the basis of the optimisation results described in Subchapter 5.1. Thus, estimating the localisation of power switches in rural, urban and average models and taking into account the amount of expenses for capital investments and impact on the parameters of reliability and losses, the optimisation was made for main and connecting lines only.

The optimisation of the number and localisation of power switches in main and connecting lines were performed with the help of genetic algorithm for the electric supply network models of average, ruraland urban areas. Capital investments and expenses for the interruption elimination without loan, for the loan period of 10 years and for the loan period of 25 years were taken in an account during optimization. For the average electric supply network model with highly reduced total duration of the interruptions and losses of the distribution network, society and customers, the optimal number of power switches was 2 items either for the loan period of 10 years or for 25 years as well as for the case without a loan period. For the urban electric supply network model with minimised total duration of the interruptions and losses of the distribution network, society and customers, the optimal number of power switches was 2 items either for 25 years of loan or for the case without a loan period. For the loan period of 10 years, the optimal number of the power switches was 3 items. For the rural electric supply network model with minimised total duration of the interruptions and losses of the distribution network, society and customers, the optimal number of power switches was 2 items either for 10 years of loan or for the case without a loan period. For the loan period of 25 years, the optimal number of the power switches was 3 items (Fig. 5.1). The total losses of the distribution network, society and customers resulting from the interruptions after the optimisation of the number and localisation of power switches and for different loan periods are given in Fig. 5.2. The benefits from the optimisation of the number of power switches are proportional to the expenses of capital investments.

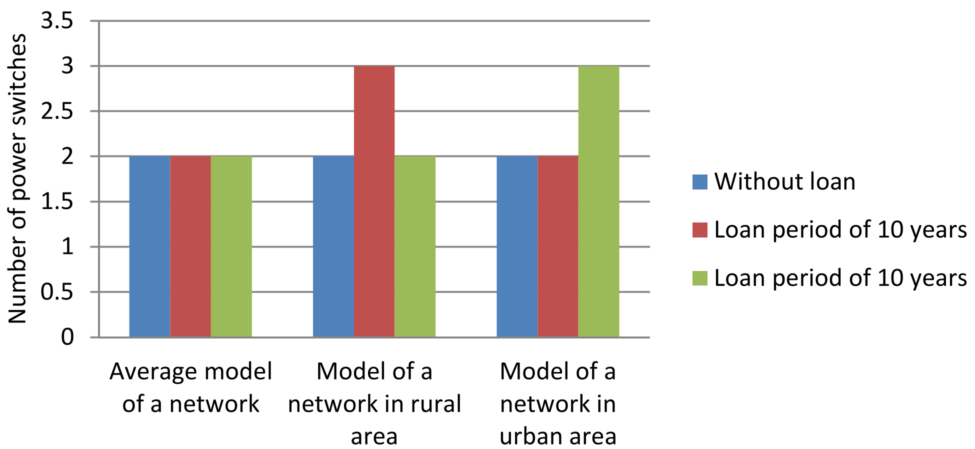


Fig. 5.1. Results of the optimisation of the number of power switches

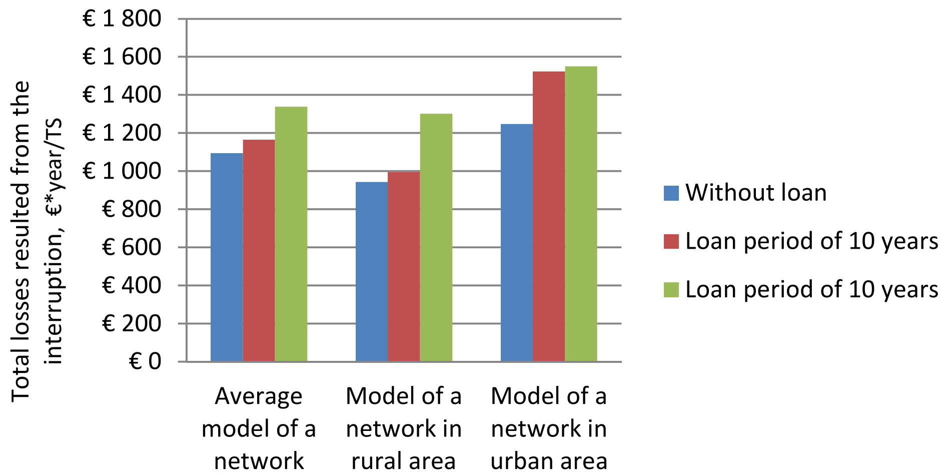


Fig. 5.2. Total losses resulting from the interruption for the case of power switch optimisation

After the optimisation of the number and localisation of power switches for the case of no loan, the losses resulting from the interruptions for the average network model were reduced by 14 %, for the electric supply network model of rural area — by 12.6 %, and for the model of urban area — by 33.6 %. Total losses from interruptions for the loan period of 10 years in the model of average network were reduced by 8 %, in the network model of rural area — by 7 %, and in the model of urban area — by 30 %. Total losses from interruptions for the loan period of 25 years in the model of average network were reduced by 5.8 %, in the network model of rural area — by 11 %, and in the model of urban area — by 20 %. Summarising the results, we can conclude that for the electric supply network models of average and rural areas the capital investments for the purchase of power switches are proportionally decreased. The total losses resulting from the interruptions are significantly decreased, as a result of sectioning for the electric supply network model of urban area. This is connected with higher consumption of electric energy in the urban regions and higher income of the customers [38].

Taking into account the total losses from the interruptions, the additional connection of power switches can be considered from the perspective of smart grid development and easy maintenance.

5.3. Results of the Optimisation of the Number and Localisation of the Breakers

The results and criteria of the optimisation of the power switches resulted in the decision to optimise the breakers in the main lines and connecting lines, taking into account the expenses of the capital investments and interruptions elimination. The optimisation of the number and localisation of breakers in main and connecting lines were performed with the help of genetic algorithm for the electric supply network models of rural, urban area and average type. Capital investments and expenses for the interruption elimination without loan, for the loan period of 10 years and for the loan period of 25 years were taken in an account during optimization.

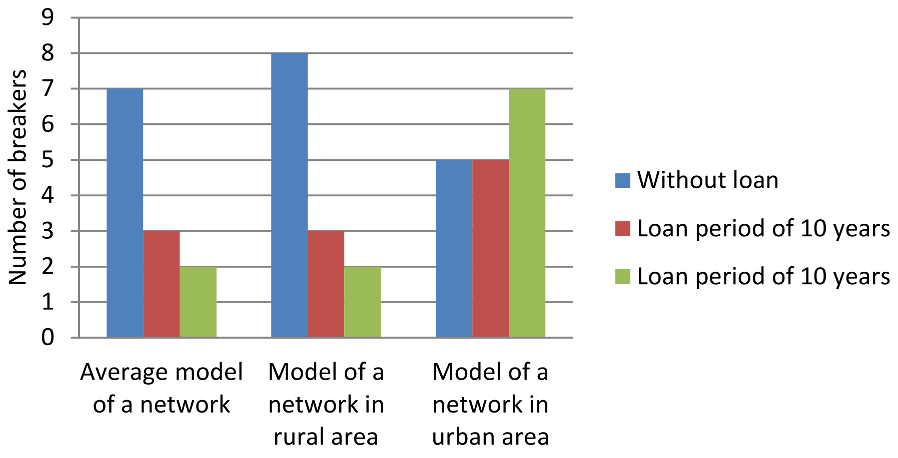


Fig. 5.3. Results of the breaker number optimisation

For the average electric supply network model with minimised total duration of the interruptions and losses of the distribution network, society and customers, the optimal number of breakers for the loan period of 10 years was 3 items, 2 items for the loan period of 25 years and 7 items without a loan. For the urban electric supply network model with minimised total duration of the interruptions and losses of the distribution network, society and customers, the optimal number of breakers was 7 items for the loan period of 25 years, and 5 items for both without a loan period and for the loan period of 10 years. For the rural electric supply network model with minimised total duration of the interruptions and losses of the distribution network, society and customers, the optimal number of breakers was 3 items for the loan period of 10 years, 2 items for the loan period of 25 years, but without the loan — 8 items (Fig. 5.3).

The optimisation of the breaker number and localisation results lead to a conclusion that without the loan it is possible to install a larger number of breakers with the same indices of the reliability.

Besides, the correspondence of the optimal number of the breakers to that of the power switches, the breakers cannot provide the operation of the network without the interruptions, that is why the minimised expenses include the customers' losses from the interruptions.

Figure 5.4 represents the total losses of the distribution network, customers and society for an optimal number of breakers for the loan period of 10 years, 25 years and without a loan.

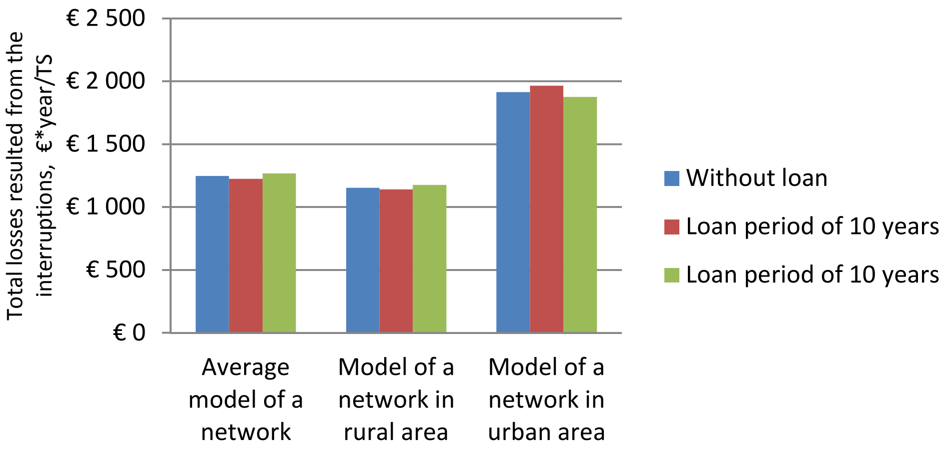


Fig. 5.4. Total losses resulting from the interruption for the case of breaker optimisation

Note that the optimisation of the number and localisation of the breakers does not give an opportunity to achieve a minimum level of the losses resulting from the interruptions.

After the optimisation of the number and localisation of breakers for the case of no loan the losses resulting from the interruptions for the average network model were reduced by 2 %, for the electric supply network model of rural area — by 1 %, and for the model of urban area — by 9 %. Total losses from interruptions for the loan period of 10 years in the model of average network were reduced by 6 %, in the network model of rural area — by 3 %, and in the model of urban area — by 9 %. Total losses from interruptions for the loan period of 25 years in the network model of average type were reduced by 8 %, in the network model of rural area — by 3 %, and in the model of urban area — by 7 %. Taking into account the total losses from the interruptions, the additional connection of breakers can be considered from the perspective of smart grid development and easy maintenance.

CONCLUSIONS AND PROPOSALS FOR FUTURE RESEARCH

The results obtained in the research prove that:

1) the overview, analysis and systematisation of the reliability calculation methods of 20 kV distribution networks, optimisation methods of reliability improvement, the alternative of the reliability improvement and the losses resulting from the electric supply interruptions give an opportunity to search for the solutions of capital investments on the level of distribution networks, customers and society taking into account the tendencies of development and perspective technologies;
2) the risks, losses, planning and advantages of the electric supply network should be analysed in accordance with economic, environment, electric supply quality, probability of interruptions, the risks of the changes in legislation, etc.;

3) the calculations of the indices of the electric supply network reliability and the value of losses resulting from the interruptions require considering the losses at the levels of customers, society and distribution networks as each of them has different topical aspects and purposes;
4) to decrease assumption application after the analysis of electric supply interruptions the process, duration frequency and probability of elimination of each interruption should also be analysed;
5) estimating the solutions of the electric supply reliability improvement, most of the attention should be devoted to the selection of optimal number and localisation of the sectioning elements that provide an immediate improvement of the electric supply reliability;
6) the factors influencing the reliability should be taken into account in the calculation of the losses resulting from the interruptions and reliability, for the scenario of the sectioning element localisation and number and for the analysis of the capital investment effectiveness;
7) the localisation of sectioning elements should be optimised before the decision making about the capital investments for a concrete object;
8) taking into account the development tendencies, analysing the reservation opportunities and comparing the solutions of different capital investment usage, the methods of reliability calculation are developed with an opportunity to change the structure and reservation;
9) taking into account the structure of the present network and tendencies of the network development, the methods of IEAR calculation, Monte Carlo and genetic algorithm have been applied for the calculation of reliability and losses resulting from interruptions, multi-criteria analysis has been applied for the accuracy of the results;
10) in the methods for the calculation of reliability and the losses resulting from the interruptions, all the elements are divided into reserving, unreserving and auxiliary elements according to a particular transformer substation;
11) the proposed methods can be applied for the calculation of the interruption risks of the customers and compensation of the losses resulting from the interruptions;
12) the possible future modifications of the proposed methods are applicable to the solutions of different problems related to the analysis of electric supply interruptions;
13) the price of the non-delivered electric energy in Latvia is close to that in other states; therefore, the duration and frequency of the interruptions can be improved estimating in detail the necessity of capital investments from the perspective of electric supply reliability improvement;
14) A–Star method and analytic calculation give an opportunity of approximate calculation of electric supply network reliability and losses resulting from the interruptions;
15) the application of genetic algorithm allows optimising the structure of electric supply network, minimising the losses from interruptions and maximising the reliability;
16) the developed Monte Carlo method of electric supply network calculation gives an opportunity to calculate the reliability and losses for a network of any complexity;
17) the results of Monte Carlo modelling are similar to the statistical parameters of a real network that proves the availability of the proposed method for the calculations;
18) the optimisation of the number and localisation of the power switches made by means of genetic algorithm without taking into account the expenses of capital investments and maintenance do not give an accurate overview about an optimal number of power switches;
19) optimisation of the number of power switches and localisation completed with the help of genetic algorithm, in accordance with the loan term and properties of the network model, allows reducing the losses from interruptions from 5.8 % to 33.6 %;

20) optimisation of the number of breakers and localisation completed with the help of genetic algorithm, in accordance with the loan term and properties of the network model, allows reducing the losses from interruptions from 1 % to 9 %;
21) the investigations of the capital investment effectiveness give an opportunity to provide higher results with as low means as possible in the reliability improvement;
22) taking into account the total losses from the interruptions, the additional connection of power switches and /or breakers can be considered from the perspective of smart grid development and easy maintenance, but not from the point of view of loss decrease;
23) the volume of the possible losses resulting from interruptions can be variable with the increasing of electric energy consumption and/or changing of the customer properties;
24) the preliminary analysis of the network is of top importance for maximum economic effect and effectiveness of the invested funds in the development program of wide sectioning device installation by JSC Sadales tīkls;
25) the optimisation of the number and localisation of the sectioning elements give an opportunity to achieve the purposes of the reliability parameters defined in the development plan of JSC Sadales tīkls for further development of the network.

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