RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
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DEVELOPMENT OF METHODOLOGY FOR POWER SUPPLY RELIABILITY LEVEL PERFORMANCE-BASED REGULATION

Summary of Doctoral Thesis

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Doctoral Thesis is proposed for achieving Dr.sc.ing. degree and will be publicly defended at 14:00 on the 29th of April, year 2013, at Faculty of Power and Electrical Engineering of Riga Technical University, 1 Kronvalda bulv., in room 117.

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CONFIRMATION STATEMENT

Hereby I confirm that I have worked out the present Doctoral Thesis, which is submitted for consideration at Riga Technical University for achieving Dr.sc.ing. degree. This work has not been submitted to any other University for achieving scientific degree.

Aleksandrs Lvovs …………………………….

Date: ………………………

The Doctoral Thesis is written in Latvian language, it contains introduction, 6 chapters, conclusions and recommendations for further work, list of references, 3 appendices, 60 figures, total number of pages is 156. The list of references includes 99 sources of information.

CONTENTS

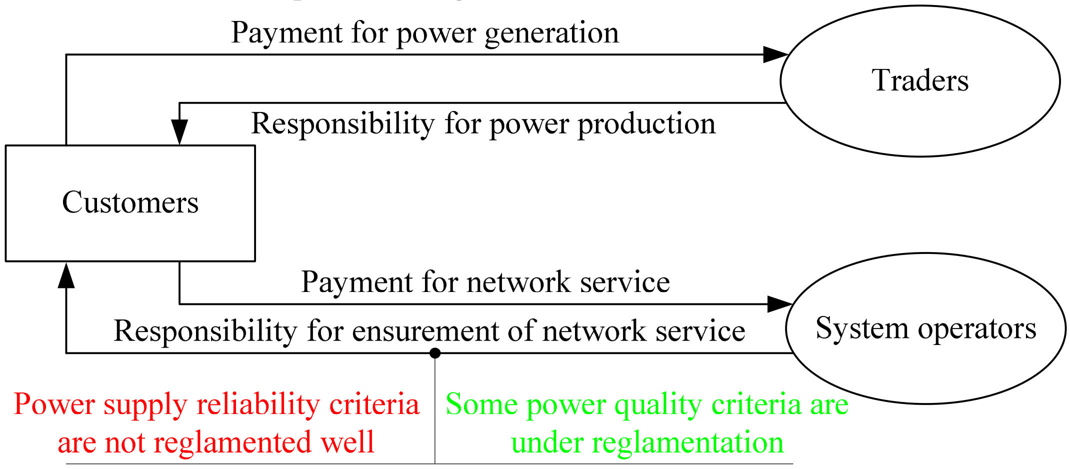
TOPICALITY OF THE WORK

Nowadays ever increasing demands for power supply reliability and quality.

National standards and regulations as well as international standards are used to determine adequate power quality level. However, unlike other power quality parameters as voltage deviation, flicker, the total harmonic distortion (THD), etc., power supply reliability index values are not specifically regulated.

Besides the above mentioned, in Latvia the system operator must ensure adequate quality of service systems and it is responsible for reliability of power system as well. In case of quality criteria violations, power users may apply for tariff discount. At the same time, the power supply reliability regulation is only applied to the power interruption time, which must be less than 24 hours. In addition, under the existing framework user himself decide on the need of some required power supply reliability level and ensure needed reliability level by implementation of additional activities on his own budget.

System operator should be responsible for quality of services in front of customers, who pay to the system operator for electricity supply/network service. Responsibility should include not only the responsibility for the aforementioned electricity quality criteria, but also for power supply reliability, which is one of the power network operation quality parameters. However, in spite of the law, the system operator's responsibility for the security of electricity supply is not specified anywhere. The current situation is depicted in Figure 1.



1. fig. Scheme of responsibilities for power supply reliability in Latvia

The above mentioned shows that there is the lack of legislation relating to the distribution system operator (hereinafter - DSO) power supply reliability obligations, which should be defined by both the power interruption frequency and duration.

To improve the existing situation, regulatory element has to be developed in order to establish the necessary level of power supply reliability, as well as incentives for system operators to achieve the required reliability level. This, as well as the lack of common problem-solving approach at the European Union level determines the high actuality of power supply reliability level regulation problem.

OBJECTIVE AND TASKS OF THE DOCTORAL THESIS

The objective of the doctoral thesis is development of methodology for power supply reliability level performance-based regulation, that would be the element of power supply reliability regulation with technical and economical basis, that is absent nowadays. Improvement of existing legislation by introduction of performance-based regulation has to encourage achievement of optimal power supply reliability level.

The optimal power supply reliability level is considered the level at which the sum of system operator and user costs related to power supply reliability is minimal. Consequently, performance-based regulation methodology has to:

- Define the most important power supply reliability indices and their usage in regulation;
- Define method for power supply reliability level estimation;
- Clearly describe the approach for power supply reliability improvement effectiveness evaluation of technical solutions;
- Include assessment of customer costs of reliability.

To achieve the objective, the following main tasks have been addressed:

1. To perform analysis of Latvian middle voltage power network reliability condition, to define topicality of power supply reliability problem;
2. To analyze approaches of power supply reliability performance-based regulation in Europe;
3. To see over power supply reliability indices and evaluate methods of their determination;
4. To study and analyze methodologies of determination of power supply interruption costs of users and develop cost assessment questionnaire for Latvian conditions, as well as perform research of power supply reliability costs involving real users;
5. Study of power supply reliability improvement technical solutions and analysis of their effectiveness;
6. To develop methodology for power supply reliability level performance-based regulation for free electricity market conditions.

The methodology has to be as scientific and practical basement, when addressing power supply reliability issues in conditions of free electricity market.

METHODOLOGY OF RESEARCH

For studies made in the frames of the thesis there have been developed and used mathematical models to assess network reliability, power supply reliability costs and analyze effectiveness of power supply reliability improvement techniques.

In power supply reliability improvement technique evaluation, minimum path set method have been used. Preference to this method was given after studying probabilistic and stochastic power supply reliability evaluation techniques.

Evaluation of power supply reliability costs of actual users have been performed using quantitative survey method and questionnaire developed by the author of the thesis. Power supply reliability costs of actual users have been gained and processed using direct worth and stated preference (contingent valuation) methods.

Tasks of doctoral thesis have been solved using Excel® and Matlab® software.

SCIENTIFIC IMPORTANCE OF THE DOCTORAL THESIS

Scientific importance of the thesis is determined by the topicality, objective and tasks.

The main existing methods for determination of power supply reliability indices have been analyzed. As the outcome of the analysis, some shortcomings of the methods have been identified. Proposed the way to overcome the shortcomings.

On the basis of research and analysis of customer power supply reliability costs evaluation methodologies, there have been developed questionnaire for obtaining power supply reliability costs of customer in Latvia. There have been obtained and evaluated real Latvian customer power supply reliability costs. Thus there have been established high value base that to be used for further research in the field of power supply reliability, as well as for further interruption (power supply reliability) cost assessment studies.

As the result of studies and analyses performed in the fames of the thesis, performance-based regulation methodology for usage by national regulatory authority have been developed. The methodology forms theoretical base for introduction of regulation and allows to make well grounded decisions from technical, economical and scientific point of view from the very beginning of regulation period.

PRACTICAL VALUE OF THE DOCTORAL THESIS

On the basis of conducted power supply interruption cost research, previously inaccessible data base for industry, commercial, public services, agriculture, transport un storage sectors have been created. The data base includes following information on the previously mentioned sectors:

- Power supply interruption costs depending on duration of interruption;
- Changes of cost values depending on interruption occurrence time;
- Used backup power supply sources and their ability to cover power consumption.

Therefore this information could be used as base for optimal power supply reliability level estimation, that allows to decrease overall costs related to power supply.

Information about power supply reliability indices have been gathered and there have been proposed several technical solutions for power supply reliability level improvement.

Proposed approach for evaluation of power supply reliability improvement solution effectiveness. Power supply reliability level calculations have been made for rural medium voltage network, to evaluate technical and economical effectiveness of reliability improvement solution – replacement of overhead lines by cable lines. Proposed approach and performed calculations of technical and economical indices could be used as example and reference for development of similar approaches and performance of calculations for other technical solutions. Proposed approach allows one to choose the most effective power supply reliability improvement solutions in real life, as well as could be used when solving network optimization tasks.

In case of implementation in real life, developed reliability performance-based regulation methodology allows to define network development way in the field of power supply reliability, regulate DSO investments and not to allow keeping inappropriate reliability level.

APPROBATION OF THE DOCTORAL THESIS

The results obtained in the frames of development of the thesis were reported and discussed at 5 international conferences:

1. Evaluation of customer costs of reliability with time-variable loads and outage costs. Riga Technical University 53rd International Scientific Conference and 1st World Congress of RPI-RTU Engineering Alumni, Latvia, Riga, 11.-12.October, 2012.
2. Analysis and Comparison of Distribution System Costs, Dependant on Underground Cable and Overhead Lines' Fault Probabilities and Maintenance Cost Difference. 12th International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), Turkey, Istanbul, 10.-14. June, 2012.
3. Assessment of Different Power Line Types' Life-Time Costs in Distribution Network from Reliability Point of View. The 8th International Conference "2012 Electric Power Quality and Supply Reliability. PQ2012", Estonia, Tartu, 11.-13. June, 2012.
4. Optimal Reliability Level Estimation for Distribution Network Considering Different Types of Load. 8th Conference of Young Scientists on Energy Issues, Lithuania, Kaunas, 26.-27. May, 2011.
5. Customer Dissatisfaction Index and Its Improvement Costs. 51st International Scientific conference „Power and Electrical Engineering", Latvia, Riga, 14. October, 2010.

PUBLICATIONS

The results obtained in the frames of development of the thesis are includes in 8 publications in international proceedings:

1. Ļvovs A., Mutule A. Customer Dissatisfaction Index and Its Improvement Costs // RTU zinātniskie raksti. 4. sēr., Enerģētika un elektrotehnika. - 27. sēj. (2010), 21.-26. lpp. (raksts pieejams EBSCO un VERSITA datu bāzēs).
2. Ļvovs A., Mutule A. Optimal Reliability Level Estimation for Distribution Network Considering Different Types of Load // Proceedings of Conference of Young Scientists on Energy Issues, Lietuva, Kaunas, 26.-27. maijs, 2011. - III-104.-III-116. lpp. (raksts pieejams INSPEC datu bāzē).
3. Ļvovs A., Mutule A. Estimation of Power Supply Interruption Related Costs. Methodology, Survey Questionnaire and Received Data Normalization // Conference Proceedings of 9th International Conference of Young Scientists on Energy Issues, Lietuva, Kauņa, 24.-25. maijs, 2012. - V-308.-V-322. lpp. (raksts pieejams INSPEC datu bāzē).
4. Priedīte-Razgale I., Ļvovs A., Rozenkrons J. Feasibility Study of Overhead Lines Replacement with Underground Cable Lines in the MV Distribution Network // Conference Pproceedings of 9th International Conference of Young Scientists on Energy Issues, Lietuva, Kauņa, 24.-25. maijs, 2012. - III-123.-III-132. lpp. (raksts pieejams INSPEC datu bāzē).

5. Ļvovs A., Priedīte-Razgale I., Rozenkrons J., Krēsliņš V. Assessment of Different Power Line Types' Life-Time Costs in Distribution Network from Reliability Point of View // Conference Proceedings (USB Media) of "The 8th International Conference "2012 Electric Power Quality and Supply Reliability. PQ2012"", Igaunija, Tartu, 11.-13. jūnijs, 2012. - 155.-162. lpp. (raksts pieejams IEEEXplore datu bāzē).
6. Priedīte-Razgale I., Ļvovs A., Krēsliņš V. Analysis and Comparison of Distribution System Costs, Dependant on Underground Cable and Overhead Lines' Fault Probabilities and Maintenance Cost Difference // Proceedings of the 12th International Conference on Probabilistic Methods Applied to Power Systems, Turcija, Istanbul, 10.-14. jūnijs, 2012. - 786.-791. lpp. (IEEEXplore datu bāze).
7. Ļvovs A., Mutule A. Evaluation of customer costs of reliability with time-variable loads and outage costs. Conference Proceedings of Riga Technical University 53rd International Scientific Conference and 1st World Congress of RPI-RTU Engineering Alumni. 11.-12.oktobris, 2012. - 1.-6. lpp.
8. Ļvovs A., Mutule A., Power supply interruption cost estimation for Latvian customers. Results of customer survey in the year 2012. // Latvian journal of physics and technical sciences, 2013. – 11 pp. Paper is submitted and approved for publication.

STRUCTURE AND VOLUME OF THE THESIS

The Doctoral Thesis is written in Latvian language, it contains introduction, 6 chapters, conclusions and recommendations for further work, list of references, 3 appendices. 60 figures, total number of pages is 156. The list of references includes 99 sources of information.

1. RELIABILITY CONDITION OF LATVIAN MIDDLE VOLTAGE NETWORK

Most of the electricity end-users are connected to distribution networks, which are made by using 20, 10 and 0.4 kV, and in some cases, 6kV and 1 kV voltage networks. Electricity is delivered to users by distribution networks of eleven licensed DSOs, but the greatest of them is JSC "Sadales tīkls" (hereinafter - ST) [1].

Electricity distribution network length is slightly more than ninety thousand kilometers. About a third (34 thousand kilometers) form medium-voltage distribution (6 - 20 kV) network, and about two-thirds - low voltage (0.4 kV) network. Every year development and reconstruction works are being performed, as well as improved power quality.

Distribution system operators shall annually provide information on some of the distribution network reliability indicators to the Public Utilities Commission (hereinafter - the PUC). Average duration of a power supply interruption per capita is one of the power supply reliability indicators characterizing reliability level. Figure 1.1. graphically illustrate average duration of a power supply interruption per capita in Latvia and European Union member states without disaster impact [2, 3].

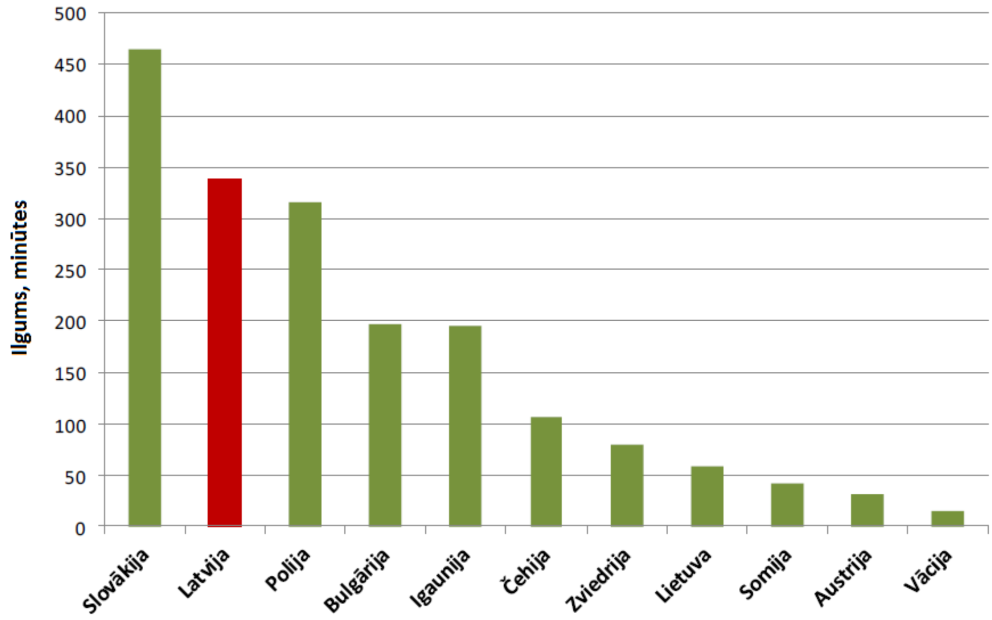


Fig. 1.1. Duration of a power supply interruption per capita, without disaster impact

As shown in Figure 1.1, Latvian electricity users experiencing relatively long power interruptions, compared to other EU countries, which in its turn may be due to different climatic conditions, differences in network structure, etc. factors. However, regardless of the possible reasons of different reliability level, it can be concluded that the problem of power supply reliability in Latvia is topical.

Power supply interruptions are divided into planned and unplanned interruptions. Duration of unplanned interruptions is highly variable, because it is influenced by size and duration of natural disaster. Planned interruption durations experiencing smaller, yet significant fluctuations. Planned interruptions are related to maintenance works in power grid, where stand-by power supply is impossible.

Analyzing ST cause damage statistics, it was concluded that data collection of some of the failure reasons is carried out without sufficient detailing. This makes it impossible to analyze interruption reasons in details and can interfere with the proper materials purchasing and operating policy choices. Also, based on analysis of the network fault reasons, it appeared that most of the damage occurs for reasons which DSO can not affect directly.

On the basis of compiled statistics of outages and comparing number of outages in Riga (the capital of Latvia) and other ST operation regions, it can be concluded that the main problem with the electricity supply exists in rural areas, where networks are built mostly with overhead lines.

As the result of reliability level research and analysis, it was concluded, that the situation in the field of power supply reliability is complex, as the greater problems with reliability exist in the major part of the network – in rural areas with large proportion of long overhead lines and relatively low density of customers. Consequently, more attention should be paid to improving the situation of distribution network of rural areas, taking into account the required power supply interruption level.

The above mentioned outlines the further research and analysis trends - existing power supply reliability performance-based regulation approaches and methodologies, choosing of power supply reliability indices and their classification, identification of technical solutions for power supply reliability level improvement and their efficiency, taking into account customer costs of reliability. The next chapters are devoted to aforementioned directions of research and analysis.

2. SUPPLY RELIABILITY LEVEL PERFORMANCE-BASED REGULATION

Taking into account monopoly state of DSOs and regulated tariffs, it is necessary to control power supply reliability indices, to reduce risks of lowering reliability level. Due to the fact, performance based regulation is performed in number of countries.

According to the report of Council of European Energy Regulators (CEER), performance based regulation is performed in at least 15 European countries [2].

The main goal of performance based regulation is to maintain or raise power supply reliability level by using economical incentives. Regulative system, in essence, creates artificial market conditions for system operators.

Incentives used in regulation can be split into bonuses and penalties and their values have to be determined on the basis of information about customer costs of reliability. Respective penalties and bonuses are applied depending on correspondence of actual reliability indices to defined target values of indices.

Number of power supply interruptions and their durations, i.e. SAIFI and SAIDI indices, usually are used as technical parameters of network reliability. Depending on threshold values of reliability indices, three zones can be identified: 1) bonus zone; 2) dead zone; 3) penalty zone (see Fig.2.1.). In case if actual reliability level is lower than smaller threshold value, SSO receives bonus. In case if actual reliability level is between thresholds (in dead zone), both penalties and bonuses don’t apply. In turn, if reliability index value is above upper threshold, system operator shall be punished with penalty [4, 5].

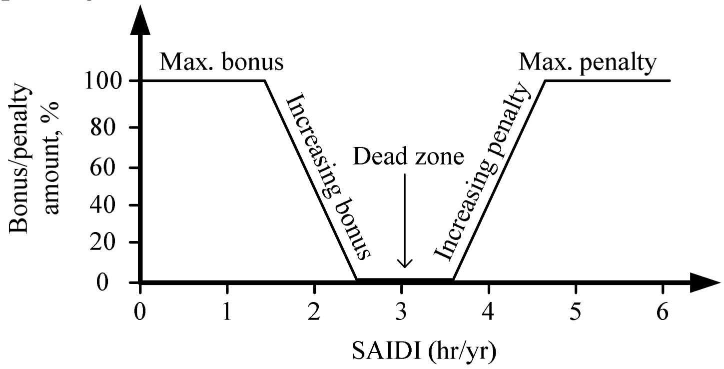


Fig.2.1. Bonus and penalty system in performance-based regulation system

It is important to identify such reliability indices’ threshold values for dead zone, that would correspond to optimal reliability level or zone of optimal reliability level. Optimal reliability level is the reliability level, at which sum of customer costs of reliability and costs of system operator, related with reliability of power supply, has minimal value.

Obviously, the theoretical basis of reliability level performance-based regulation methodology is relatively simple. However, the practical implementation of the regulation could face a number of challenges, such as the appropriate bonus /

penalty amount identification and changes depending on the level of reliability, thresholds of reliability indices for regions of country (network regions), defining separate country regions (network regions), etc..

Approaches of performance-based regulation of the following 16 European countries have been analyzed: Bulgaria, Denmark, Finland, France, Great Britain, Hungary, Ireland, Italy, Lithuania, Netherlands, Norway, Portugal, Slovenia, Spain, Estonia. The analysis was based on information on existing regulations from state regulators, as well as from individual experts [2, 6-9].

Analyzing national regulation approaches, it is concluded that at present there is no common approach for implementation of regulation, that would be focused on the achievement of optimal power supply reliability. At the moment, most of the methods of performance-based regulation approaches objectively unable to provide optimal reliability level, at least so that the required level of power supply reliability is determined on the basis of other national power network reliability levels, rather than on costs of system operators operating in the country and customer costs of reliability.

In order to implement reliability level performance-based regulation that would facilitate the optimal reliability level achievement and maintenance, there have to be identified power supply reliability indices appropriate for regulation. Values of reliability indices, that have to be taken into account in regulation, should be identified as well. Besides reliability indices, different reliability level targets have to be set and justified for different country regions, and the need to control and regulate power supply reliability level for individual users should be identified too. Another crucial prerequisite for performance-based regulation introduction is carrying out customer cost assessment study, that allows to identify appropriate amount of bonus/penalty. Reliability level performance-based regulation will ensure that national regulatory authorities and system operators will have common understanding of the possibilities how power supply reliability can be improved, of the assessment of the costs needed for reliability improvement activities, as well as evaluation of effectiveness of the activities.

3. ANALYSIS OF POWER SUPPLY RELIABILITY INDICES

Number of indices (indexes) have been developed and applied for power supply reliability assessment. Not all of them are being used by energy companies, but those that are used, often contain information evaluated by different approaches.

Power supply reliability for a particular network point is described by three basic load point indices, but reliability of network or whole region – with a range of system reliability indexes.

This chapter deals with load point and power system indexes. Methodologies for dividing all values of power system reliability indexes into normal and major event day values have been analyzed too.

When calculating values of power system reliability indexes, information about long-term power supply interruptions is used. There are also special indexes that use short-term power supply interruptions. The following indexes have been studied and analyzed in the thesis:

- SAIFI (System average interruption frequency index).
- SAIDI (System average interruption duration index).
- CAIDI (Customer average interruption duration index).

- MAIFI (Momentary average interruption frequency index).
- CTAIDI (Customer total average interruption duration index).
- CAIFI (Customer average interruption frequency index).
- ASAI (Average service availability index).
- ASIFI (Average system interruption frequency index).
- ASIDI (Average system interruption duration index).
- EENS (Expected energy not supplied).
- ECOST (Expected interruption cost).
- IEAR (Interrupted energy assessment rate).

On the basis of analysis, the author of the thesis believes that in performance-based regulation there should be used not only SAIDI and SAIFI indexes, but also CAIDI index that allows to assess customer costs of reliability more precisely. It would also be appropriate to use MAIFI index, because short-term interruptions are topical for large number of customers.

In addition to differences related to the geography of the network, power supply reliability index values may vary depending on the data collection and processing techniques and methodologies, as well as practices established in utility. Different time thresholds used to define long-term and short-term power interruptions leave an effect on the values of power supply reliability indexes, too.

The main difficulty may arise in relation to the so-called "major event days" exclusion from information collected on reliability indexes. Exclusion of such values of reliability indexes is important when trying to evaluate real changes of power supply reliability as result of activities of system operator for maintaining or improving power supply reliability level. This is especially important in cases of reliability level performance-based regulation, because planning technical activities and making investments into the network, system operator shall take into account regionally specific natural conditions and other factors that have certain regions of the country.

When analyzing power system reliability, system operators usually evaluate values or reliability indexes that include all events, as well as after data processing, separate normal days from days with „major events” [4]. The term „major event day” is used to separate power supply interruptions caused by emergency situations from the rest power supply interruptions. Latvian larges distribution system operator – ST, divide values of power system reliability indexes into two categories – „with impact of natural disasters” and „without impact of natural disasters”. The first of these occurs in cases where the ST staff of one operating district is not likely to eliminate power supply interruptions within 24 hours.

In the thesis there have been discussed and analyzed in IEEE Standard 1366-2003 offered 2.5 Beta method for major event day exclusion, that is used in USA and two step method that is used in Italy, which is just slightly modified 2.5 Beta method. In addition to above mentioned methods, Bootstrap and 3 Sigma methods have been discussed and analyzed [10-16]. In the frames of the thesis, values of SAIDI for normal and major event days have been estimated by IEEE and ST method for four years 2009-2012.

It is concluded, that despite the definitions of reliability indexes used in standards, laws and regulations, it is hard to compare reliability levels between countries because of different ways of information collection, as well as various national and regional climatic conditions and network design specifications. Also found that none of the described methods for the determination of major event days does not allow to estimate values of indexes completely correctly. As one of the solutions to the problem of major event days' detection could be usage of information about obstacles to grid power system operators to start restoration work, as well as information on third-party action, which led to a power cut situation, together with statistical information on interruptions.

4. ASSESSMENT OF ECONOMIC EFFECT OF POWER SUPPLY INTERRUPTIONS

One of the requirements for power network is efficiency – network should provide electricity at the lowest possible cost. Efficiency of the network can be evaluated from power and energy losses point of view, construction costs, but also can be evaluated from point of view of customer costs of reliability and costs of power system operator related with reaching and maintaining some reliability level. Amount of customer costs related with power supply interruptions, as well as system operator costs depend on network reliability level. Consequently, network reliability level serves as one of the criteria for assessing the effectiveness of the network, at which customer and system operators costs should be at optimal/balanced level.

To develop reliable and secure power supply reliability regulation methods, sufficient information about power supply interruption costs of customers is very important.

In order to evaluate power supply interruption costs of customers a variety of methods can be used. In this chapter methods of assessment of customer costs of reliability have been analyzed and systematized. Direct worth and contingent valuation (direct measurement of willingness to pay or willingness to accept) methods have been studied in detail and used by the author for study of customer costs of reliability in Latvia. Analysis of the data from the study, as well as their comparison with results from other countries have been performed, too.

Before the study, existing customer groups have been identified, as well as studied and analyzed methods of monetary losses (cost) estimation, which are categorized at figure 4.3. [26-30]. As mentioned above, detailed attention was paid to two of the methods, that are the most common methods of estimating costs in commercial and industry sectors – the total share of usability of these methods is respectively 62% and 60%.

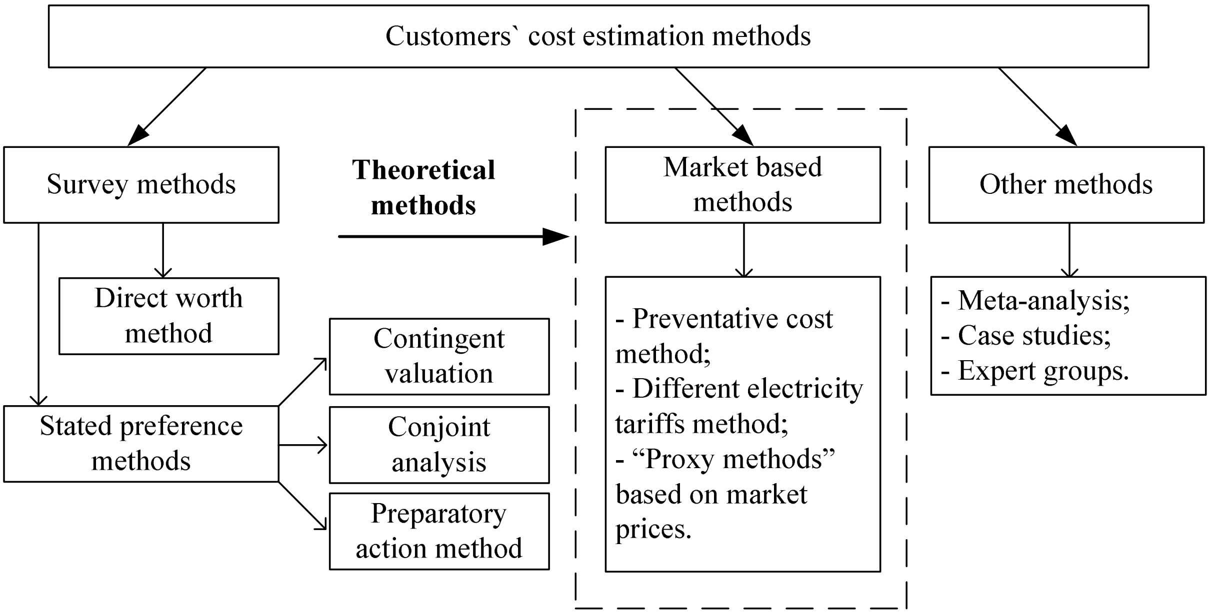


Fig. 4.3. Categorization of cost estimation methods

Survey based methods have been chosen for the study, because users themselves are more aware of the costs of power supply interruptions.

Incidents with power supply reliability during the recent years (2010 to 2012), that led to power supply interruptions for big amount of customers, formed the basis for inclusion of customer cost of reliability and compensation mechanisms topics in Latvian Government Action plan for the year 2012. Implementation of the study was planned because the last known such type study in Latvia until year 2012 have been performed in 1976.

Due to the lack of information and previous studies, additional objective of the study was to get as much information, related to customer costs of reliability, as possible in existing time and financial constraints of the study.

The way of survey conduction – using internet resources (letters with questionnaire have been sent to customers by e-mail), was chosen as the optimal option among number of the survey conduction possibilities because of aforementioned constraints.

Groups of respondents for the survey were selected using the NACE Rev. 2. classificator according to the study objectives, and taking into account analysis of foreign research results, which showed the largest customer costs in industry, commercial and public service sectors.

Questionnaire used in the study was prepared in suitable form for Latvian conditions and situation. Number of factors have been taken into account, starting with features of cost estimation methods, that allow to increase the plausibility of the results obtained, and finishing with the data required for normalization of obtained results.

The number of respondents involved in the Latvian study have been chosen on the basis of study of abroad experience, as well as forecasting expected activity of respondents in Latvia.

Further there is given short description of the study and main results.

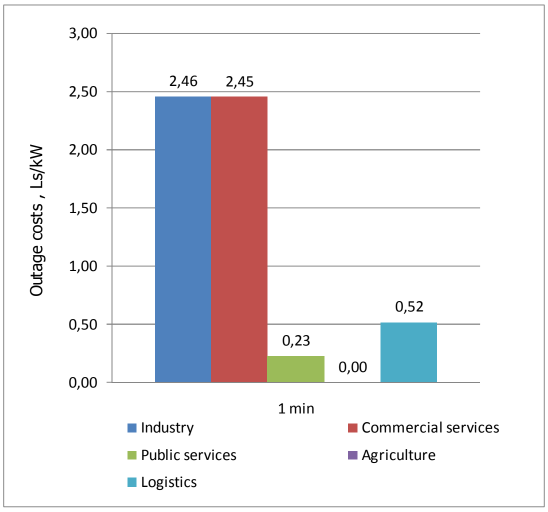
The study began in July 2012 with sending of questionnaires to 3000 respondents. After a certain time reminder letter was sent to the respondents, that have not been given response. The next study step was to collect and process received results, followed by analysis of the data.

Respondents activity was lower than the planned 10%. In overall 240 questionnaires were received, representing approximately 8% of all survey participants. In addition, much of the questionnaire were discarded because they were filled only partially, and did not provide sufficient information. Only 111 questionnaires from 240, or 46%, were filled in an appropriate way in order to be used. Distribution of usable questionnaires by sectors is following: industry - 34 questionnaires, commercial services - 30 questionnaires, public services - 41 questionnaire, Agriculture - 2 questionnaires, Logistics - 4 questionnaires. Thus, it can be stated that the effective activity of respondents is just 3.7%.

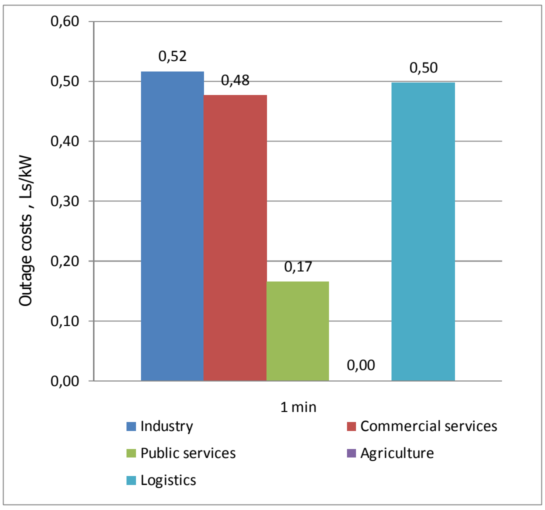
The results of the study on customer costs of reliability have been divided into two parts – customer costs of reliability due to short-term power supply interruptions (costs due to interruptions with duration <3min.) and costs due to long-term interruptions.

Obtained values of customer costs have been normalized with generally accepted normalization factors, using both customer typical load curves with data from questionnaire and real customer load curves. As the result of data processing customer damage functions (CDF) have been received.

Figure 4.9. gives momentary outage costs for five customer sectors. The results shown in figure 4.9. a) have been normalized with load interrupted at reference time, but in figure 4.9. b) – with maximal allowed power. Value of load interrupted at reference time have been estimated using information on maximal allowed power and typical load curve of corresponding customer [33]. For determination of normalization factor values for short-term and long-term interruption cost values along with typical load diagrams, real load diagrams of 46 customers have been used.



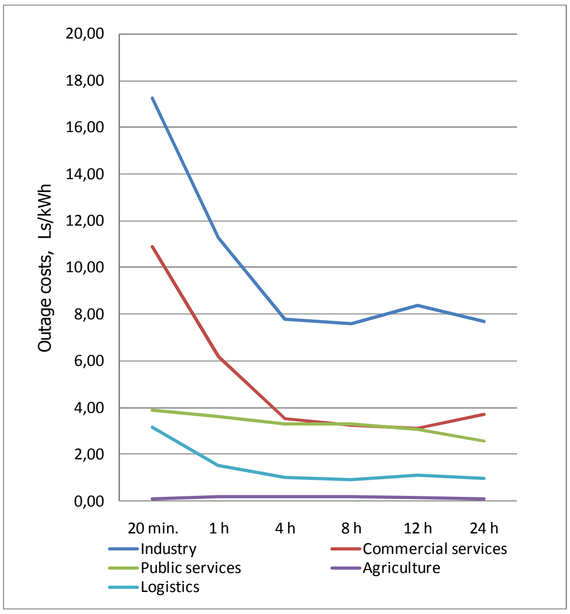
a)



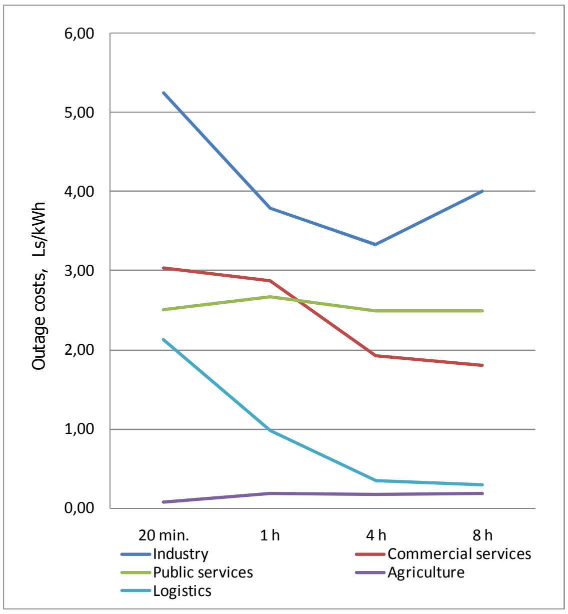
b)

Fig.4.9. Momentary outage costs. Cost values normalized: a) with load interrupted at reference time; b) with maximal allowed power

Figures 4.10.a) and 4.10. b) show outage costs normalized by energy not supplied, caused by unplanned and planned power supply interruptions, respectively. Value of energy not supplied, similarly to load interrupted at reference time for momentary outages, have been estimated using typical and real load diagrams.



a)



b)

Fig. 4.10. Outage costs, normalized by ENS, caused by: a) unplanned power supply interruptions; and b) planned power supply interruptions

Information about reduction of outage costs in case of planned interruption comparing to unplanned interruption has been observed too. All sectors, with the exception of agriculture sector, that didn't show any reduction in costs, showed sharp drop in losses – from 25% to 70% at interruptions with duration not longer than 8 hours.

In addition to customer damage functions, cost change curves have been obtained, that show changes of outage costs depending on the season, day of the week or time of day at which power supply interruption occurred. Changes of outage costs depending on season are showed at figure 4.13.

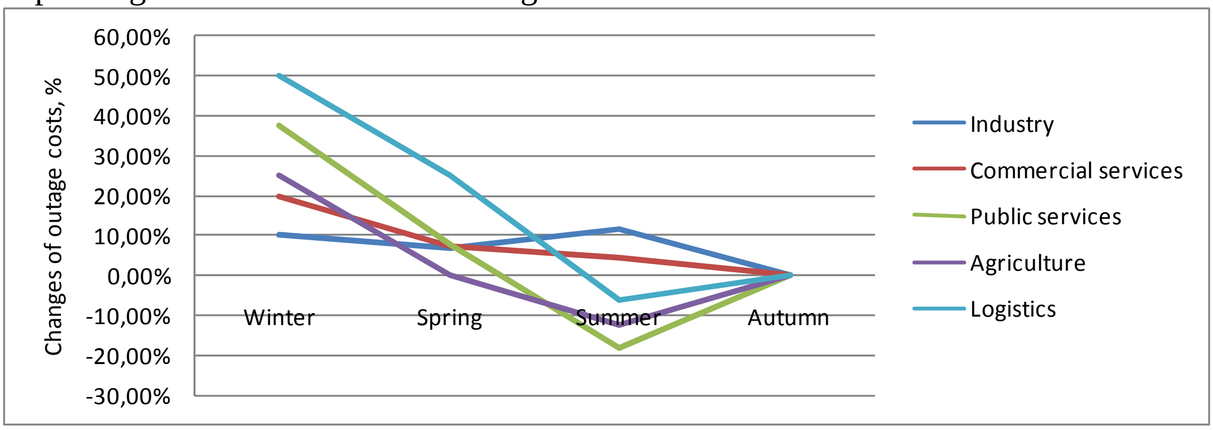


Fig. 4.13. Changes of outage costs depending on season

In the frames of the study, information about existence of backup power source, it's type and ability to provide power supply have been gathered too.

Processing of foreign research data made it possible to compare results of Latvian study with the results of foreign studies. Comparison of customer damage functions' shape showed their correspondence to the results of foreign studies.

Using results of the Latvian study it is possible to assess the number of respondents that have to be involved in further similar studies. The assessment can be done using equations (4.2) and (4.3), but with the condition that the results of the study have normal (Gaussian) distribution [27, 34].

$$n = \left(\frac{S \cdot 2 \cdot Z}{L} \right)^2 \tag{4.2}$$

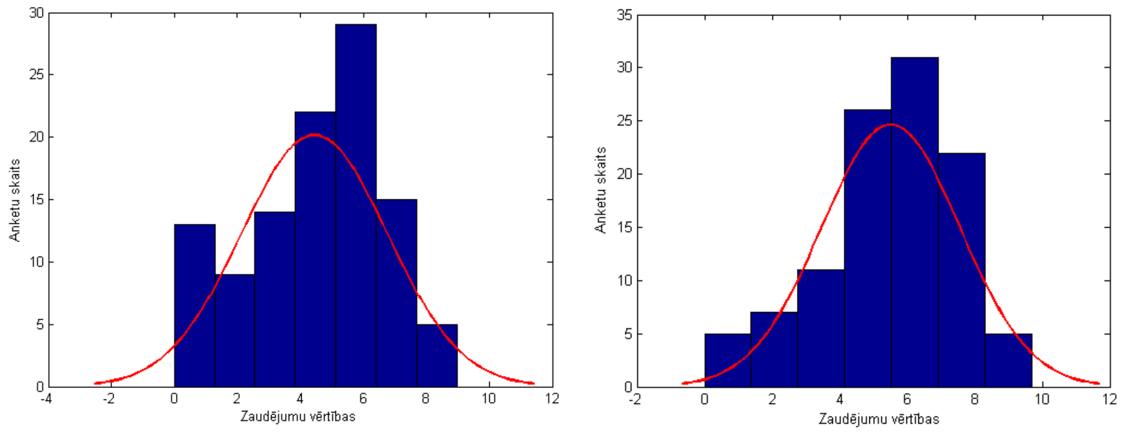
n – number of respondents needed;
S – standard deviation;
Z – Z-value depending on the distribution and the confidence level;
L – Length of the confidence interval.

The number of respondents, that should be involved in the study, is calculated using equation (4.3).

$$N = \frac{n}{R} \tag{4.3}$$

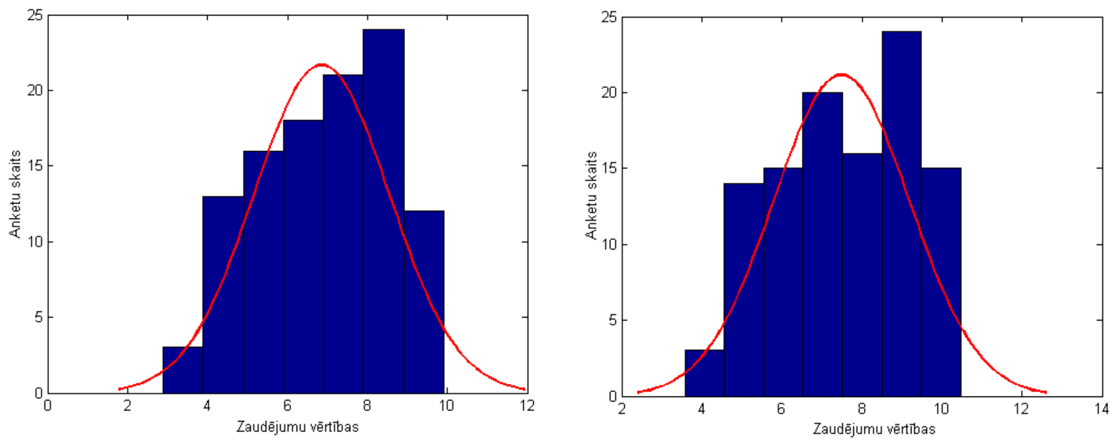
N – Sample size
R – Response rate

As customer costs can have only positive values, they cannot have normal (Gaussian) distribution. While distribution of customer costs value logarithms can match normal distribution. After cost data processing, distributions of customer costs for interruptions with durations 20 minutes, 1, 4, 8, 12, and 24 hours have been obtained. Obtained distributions are given at figures 4.22, 4.23, 4.24.



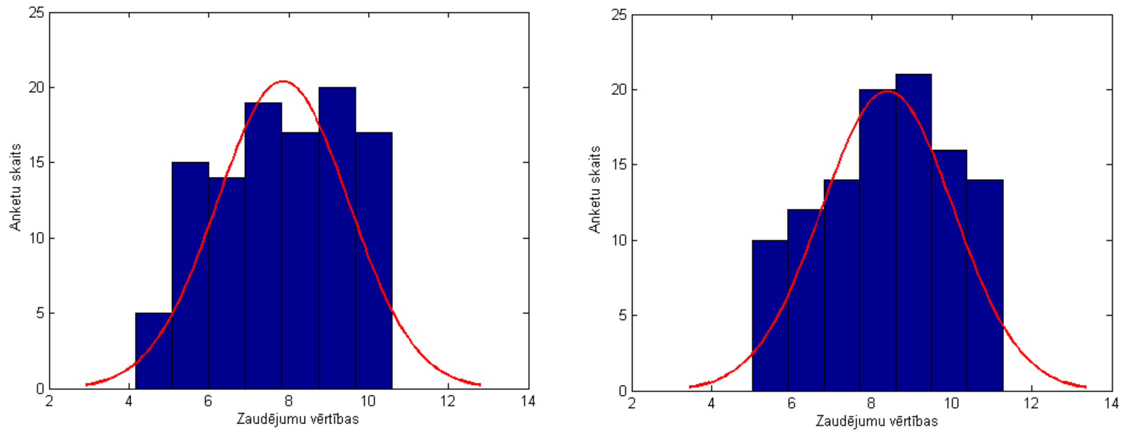
a) b)

Fig 4.22. Distribution of customer costs for interruptions with durations: a) 20 min.; b) 1h



a) b)

Fig 4.23. Distribution of customer costs for interruptions with durations: a) 4h; b) 8h



a) b)

Fig 4.24. Distribution of customer costs for interruptions with durations: a) 12h; b) 24h

At the three previous figures at X axes showed customer costs, but at Y axes – number of questionnaires that corresponds to the cost interval. As can be seen from the pictures, distribution of results is close to normal distribution, especially taking into account number of usable response. Due to the fact it is possible to assess the number of respondents that have to be involved in further studies.

To assess number of respondents that have to be involved in further study, standard deviation S of the existing study results, Z value, depending on the distribution and the confidence level, as well as wanted confidence level and confidence interval length should be known.

Table 4.5. summarize results of calculations that show number of questionnaires to be sent to receive survey results that would lie in interval ±5% of average value of results with probability of 95%. Results in Table 4.5. take into account low response rate of Latvian study.

Table 4.5.

Number of questionnaires that have to be sent

	Duration of power supply interruption					
	20 min.	1 h.	4 h.	8 h.	12 h.	24 h.
Number of questionnaires	11359	5772	2537	2140	1825	1599

Taking into account that average duration of unplanned power supply interruption in Latvia in the years 2009-2011 was 3.13 hours, it can be seen that for Latvian study presented in the thesis there was selected an appropriate number (3000) of respondents – that lies between 5771 respondents (for 1h long interruption) and 2537 respondents (for 4h long interruption). This ensures high plausibility of the results.

5. RESEARCH AND ANALYSIS OF POWER SUPPLY RELIABILITY IMPROVEMENT TECHNICAL SOLUTIONS

This chapter is dedicated to analysis of power supply reliability improvement technical solutions. The first section of this chapter deals with methods for estimation of reliability parameters. Using these methods it is possible to determine changes of reliability parameters under different scenarios of network development. For reliability level improvement at distribution network level there should be used methods that are cost-effective and allow achieving optimal reliability level. Consequently, the chapter also dealt with the customer and system operator costs, developing and offering algorithms for determination of customer and system operator reliability related costs volumes. In the third section power supply reliability improvement technical solutions have been studied. While in the fourth section have been made detailed power supply reliability improvement calculations for one of the power supply reliability improvement technical solutions.

Methods for estimation of reliability parameters

For estimation of reliability parameters deterministic assessment, or analytical estimation techniques, and probabilistic, or simulation assessment techniques, that are gaining popularity in recent times due to computer productivity growth, can be used.

Probabilistic assessment of reliability parameters was developed based on the fact that the outages have probabilistic nature and therefore probabilistic method can better reflect real process. Popularity have gained so-called *Monte Carlo simulation methods*.

Essence of Monte Carlo simulation methods' calculation process is given in figure 5.3. [17]. Random numbers are used for determination of values of network elements' reliability parameters (in figure 5.3. marked as *Y(t)*). When values of elements' reliability parameters are known, the final result is obtained based on the data about system – system structure, that determines interaction of elements. Performing calculations with Monte Carlo methods, different result values are received at each calculation cycle. Therefore it is usually made sufficiently large number of iterations, at which the results vary in limited range.

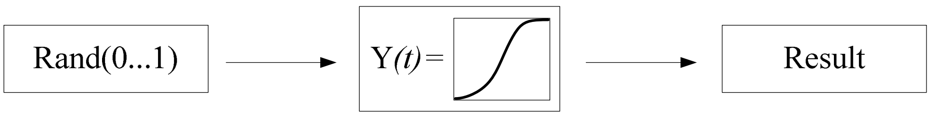


Fig. 5.3. The essence of Monte Carlo simulation methods

Using power supply reliability analytical estimation techniques, power system is presented in the form of mathematical model to evaluate reliability parameters through direct numerical techniques. In cases where the system is not big, the calculation process takes relatively little time. Analytical techniques are discussed and described in detail in the books and are used when creating standards in the field of power supply reliability [18-20]. Given the fact that actual power systems are typically complex, usage of analytical techniques for reliability level estimation requires simplification of the real system (usage of network reduction methods) before calculation begins.

One of the network reduction methods is *Minimum tie set method* (also known as minimum path set method). Minimum tie set includes components of the analyzable network, that altogether form a continuous link between the power source (system) and load (load point).

Another network reduction method is *Minimum cut set method*. A cut set is defined as a set of elements that, if fails, causes the system to fail regardless of the condition of the other elements in the system. A minimum cut set is one in which there is no proper subset of elements whose failure alone will cause the system to fail.

Research of Monte Carlo methods showed that results obtained with these methods converge in wide range of number of iterations, that can be explained by usage of different Monte Carlo approaches. For example, calculating loss of load probability (LOLE) values, results converge after about 600 iterations and match with results of obtained by analytical method (see Fig.5.5.) [21]. Similar situation is illustrated in dissertation of Peng Wang “Reliability Cost/Worth Consideration in Distribution System Evaluation”, where value of reliability parameter, using sequential simulation, converged with values obtained by analytical simulation after 1700-200 iterations [22]. Estimation process of power system reliability indices (SAIDI, SAIFI, etc.) also showed similar results.

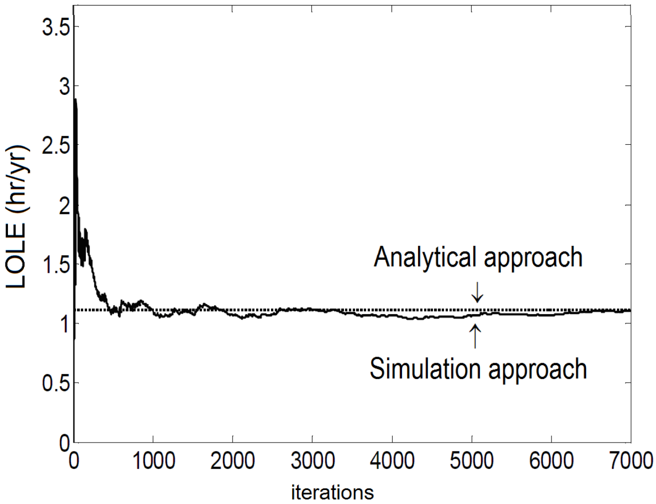


Fig. 5.5. Calculation of LOLE value using analytical and simulation approaches

Taking into account development of computers and calculation approaches that allow achieving faster convergence, probabilistic reliability assessment approach could be implemented easily enough. However, its application has some disadvantages associated with sufficiency of detailed statistical information on equipment outages for choosing respective type of statistical distribution and high costs of software for calculations [20]. Given the fact that comparing with analytical approach, probabilistic approach needs much more detailed equipment failure statistics, and the fact that for application of analytical approaches, reduced (typical) network schemes can be used, preference to be given to analytical reliability assessment.

Assessment of customer costs of reliability taking into account time-variable costs and loads

When examining time-variable loads and attributed costs related to power supply interruptions of industry and commercial sectors, it was concluded, that correlation between these values can exist, but in some cases correlation may not exists [23-25].

In case if correlation between the values is low or don’t exist and if information about customer load curves is available, both time-variable loads and costs should be taken into account.

For the process of evaluation of total volume of customer costs of reliability, that takes into account energy not supplied (ENS) and changes of attributed costs are known, author of the thesis developed the algorithm for sequence of operations. The algorithm is shown in figure 5.12

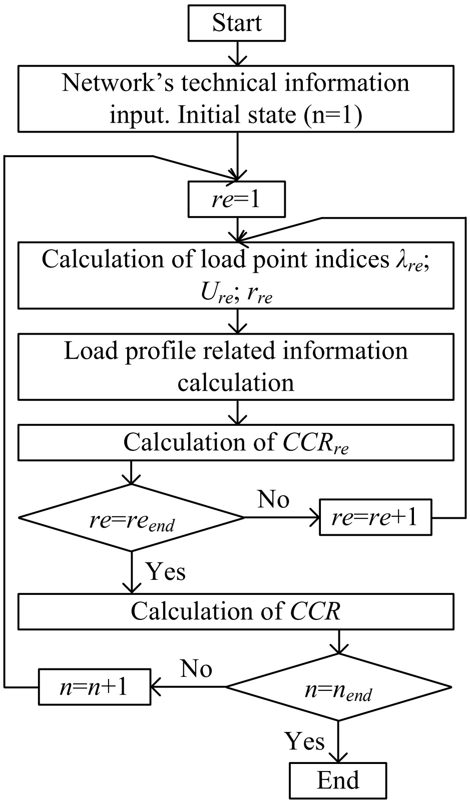


Fig. 5.12. Algorithm for sequence of operations for the process of evaluation of total volume of customer costs of reliability

According to the proposed algorithm, before evaluation of customer costs, information about network and its reliability is prepared for operation regime *re=1* at network initial state *n=1*. ENS and interrupted power at power supply interruption time is calculated on the basis of load point information. After information is prepared, volume of customer costs of reliability for regime *re*, that determines load diagram of customers according to season, day of week and time of day, can be calculated. Calculation cycle repeats until all regimes are covered. In case if several network configurations are being compared (for example network with cable lines and overhead lines), network state number *n* changes and calculations for new network state start from the beginning.

Calculation of total volume of customer costs of reliability for short-term and long-term power supply interruptions is made according to equations (5.1) and (5.2) respectively.

$$CCR_s = \sum_{re=1}^{re_{end}} \frac{h_{re}}{8760} \cdot \left[\sum_{f=1}^{F} \sum_{lpf=1}^{LPf} \cdot \left(\frac{\sum_{i=1}^{z} P_{re,lpf,i} \cdot h_{lpf,i} \cdot C_{s,re,lpf,i}}{24} \cdot P_{\max,lpf} \cdot \right.\right.$$

$$\left.\left. \cdot \left(\sum_{L=1(L\in M_{Lf})}^{L=lpf-1} \cdot \lambda_{Ls,re} + \sum_{L=lpf\,(L\in M_{Lf})}^{L=lpf} \cdot \lambda_{Ls,re} + \sum_{L=lpf+1(L\in M_{Lf})}^{L=LPf} \cdot \lambda_{Ll,re} \right) \right) \right] \quad (5.1)$$

where
CCR_s – customer costs of reliability caused by short (< 3 min.) power supply interruptions [monetary units].
re – network regime that affects load diagrams of load points and failure rates of network elements.
re_{end} – total number of network working regime.
h_{re} – duration of working regime re during year [h].
f – number of feeder.
F – total number of feeders f connected to substation.
lpf – number of load point of the feeder f.
LPf – total number of load points on a feeder f.
i – number of time interval of a day that corresponds to specific costs of load interruption.
z – total amount of time intervals of a day.
$P_{re,lpf,i}$ – average active load in % of maximal active load, that corresponds time interval i of the load point lp on a feeder f during regime re [%].
$h_{lpf,i}$ – duration of interval i that corresponds to specific costs of power supply interruption in load point lp on a feeder f [h].
$C_{s,re,lpf,i}$ – costs of short power supply interruption (< 3 min.) in time interval i of the load point lp on a feeder f during regime re [monetary unit/kW].
$P_{max,lpf}$ – max. active load of load point lp of feeder f [kW].
L – number of feeder section.
M_{Lf} – set of sections that form a feeder f.
$\lambda_{Ls,re}$ – failure rate (for short outages) for section L in regime re [short outage/km year].
$\lambda_{Ll,re}$ – failure rate (for long outages) for section L in regime re [long outage/km year].

$$CCR_l = \sum_{re=1}^{re_{end}} \frac{h_{re}}{8760} \cdot \left[\sum_{f=1}^{F} \sum_{lpf=1}^{LPf} \cdot \left(\frac{\sum_{x=1}^{24} ENS(t_{repair})_{re,lpf,x} \cdot C(t_{repair})_{l,re,lpf,x}}{24} \cdot \sum_{L=1(L \in MLf)}^{L=lpf-1} \lambda_{Ll,re} + \right.\right.$$
$$+ \frac{\sum_{x=1}^{24} ENS(t_{repair})_{re,lpf,x} \cdot C(t_{repair})_{l,re,lpf,x}}{24} \cdot \sum_{L=lpf(L \in MLf)}^{L=lpf} \lambda_{Ll,re} +$$
$$\left.\left. + \frac{\sum_{x=1}^{24} ENS(t_{switch})_{re,lpf,x} \cdot C(t_{switch})_{l,re,lpf,x}}{24} \cdot \sum_{L=lpf+1(L \in MLf)}^{L=LPf} \lambda_{Ll,re} \right) \right] \tag{5.2}$$

where
CCR_l – customer costs of reliability caused by long (> 3 min.) power supply interruptions [monetary units].
$ENS(t_{repair})_{re,lpf,x}$, $ENS(t_{switch})_{re,lpf,x}$ – energy not supplied for load point lpf in case if power supply interruption occur at time x of a day [kWh].
$C(t_{repair})_{l,re,lpf,x}$, $C(t_{switch})_{l,re,lpf,x}$– costs of energy not supplied for load point in time of power supply interruption start hour x in regime re [monetary units/kWh].

Equations (5.1) and (5.2) are used for radial network structure. Backup power supply possibilities of feeder don't have effect on short-term costs, because connection to backup power source is made if interruption is longer than 3 minutes. Due to that equation (5.1) can be used also for looped feeder. In case of calculations for long-time interruptions for looped feeder, time t_{repair} of the first element in round parentheses has to be replaced by time t_{switch}.

Power supply reliability improvement technical solutions for distribution network

The most popular indexes for power supply reliability evaluation of distribution network are SAIDI and SAIFI indexes. CAIDI and MAIFI indices also should be used for evaluation of effectiveness of technical solutions. Usage of these indexes shows the ways of power supply reliability improvement technical solutions:

- Reduction of number of interruptions;
- Reduction of interruption time;
- Reduction of number of affected customers.

In the thesis there are given technical solutions for each of the ways and have been performed their evaluation.

In the section it was arrived to the conclusion that ability of technical solution for power supply reliability improvement is strongly dependent of the network structure and configuration and that solutions can complement each other. Effect of technical solutions on system reliability indexes – like SAIDI, SAIFI, etc. – also depends on distribution of customers over the network. Therefore efficiency of each of the solutions should be assessed in detail looking at specific examples of the network. Selection of one or another technical solution for network should be done not only on the basis of technical calculations, but also in the context of economical effect.

Number of actual power supply reliability improvement solutions proposed for distribution system operator JSC „Sadales tīkls" have been evaluated taking into account information both on their economical measures and expected return on their implementation.

Each of the technical solutions has different efficiency of investment, i.e. each of the solutions has different output in reliability improvement for each invested money unit. However these solutions can't be evaluated looking only at capital investments and improvement of a single reliability index. Analysis has to take into account several reliability indices that are in use, as well as maintenance and fault elimination costs. For example, replacement of overhead lines with cable lines require relatively big investments from perspective of SAIDI value reduction, but usage of cable lines helps to reduce not only number of long-term interruptions, but also number of short-term interruptions and system operator costs for cleaning line's protective zone.

It is still worth to remember, that it is useful to improve reliability level only up to certain level, after which the improvement of reliability is no longer justified.

Technical and economical study and analysis of power distribution overhead lines replacement with underground cable lines.

In the thesis there is also proposed algorithm for technico-economical assessment of overhead lines replacement by underground cable lines, that is one of the most actual questions in the field of power supply reliability improvement in Latvia. The goal of proposed algorithm is to evaluate changes of costs of system operator when implementing aforementioned activity. The sum of customer and system operator costs gives the indication of the effectiveness of particular power line type from power supply reliability point of view.

For case study it was used medium voltage network scheme that takes into account typical structure of rural medium voltage distribution networks used in Latvia (see figure 5.13.). Network structure is based on information from Latvian biggest distribution system operator JSC „Sadales tīkls" [35]. It was assumed that feeder section L1 and corresponding branches are placed in field, feeder section L2 and corresponding branches are placed along roads, feeder section L3 and corresponding branches are placed in forest.

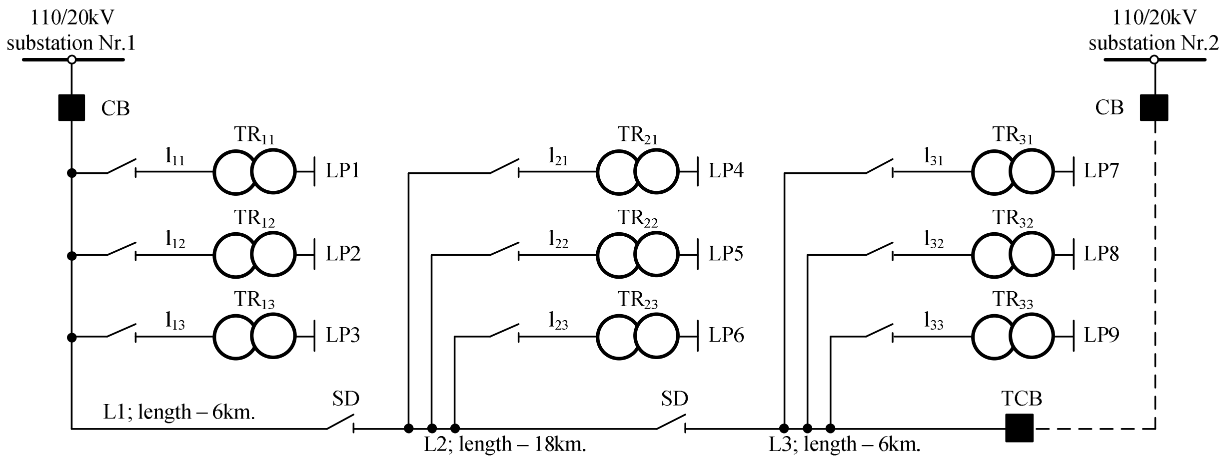


Fig. 5.13. Medium voltage distribution network

Information on cable line outages have been taken from distribution system operator JSC „Sadales tīkls" statistics, but information on overhead line outages have been taken from the publication of Tampere Technical University scientists, where number of outages have been given depending on overhead line placement – in field, in forest or along road [36].

Evaluation of customer costs

Customer costs evaluation was performed according algorithm given in this chapter previously, but replacing individual customer load diagrams with average loads of customer sectors, that have been taken for each of year seasons, as well as for working days and holidays. Information about Latvian customer costs from the study performed in the thesis and resulted in the previous section has been used here too.

In the calculations there have been used statistical data about customer sectors` energy consumption and typical load diagrams of the sectors` customers [33, 37, 38]. It was assumed that at each load point there are 100 customers that have total maximal power of 450kW.

Calculations have been made separately for four seasons and separating working days and holidays. Taking into account that customer costs depend also on power supply interruption duration, there was used Latvian typical fault elimination time for medium voltage networks, which, according to the information from journal "Energy forum", in summer 2011 was 7 hours and 7 minutes [39]. Switching time – 1 hour – have been also used in power supply reliability calculations, as network scheme contains several switching apparatus.

Assessment of distribution system operator costs

Costs of system operator related with power supply lines consist of capital costs, or line construction related costs, maintenance costs that include also preventive repair costs, as well as fault elimination costs. To compare network alternative construction options, previously mentioned costs are being calculated for one year of line life. The total costs come from the sum of the three above-mentioned costs in accordance with equation (5.3).

$$C = \sum_{i=1}^{n} (C_i + C_{mi} + C_{fe.i}) \tag{5.3}$$

where

C – total costs of network for some period of time [monetary units/time period];

C_i – total construction costs of lines with parameters i [monetary units];

C_{mi} – total preventive repair/maintenance costs of lines with parameters i [monetary units];

$C_{fe.i}$ – total fault elimination costs for lines with parameters i [monetary units];

i – number, corresponding to power line with specific parameters;

n – total number of lines with different parameters used for the network.

Analyzing and researching system operator costs related with construction and maintenance of a power line, algorithm for cost assessment, as well as equations for calculations, have been developed and proposed. Proposed algorithm can be seen at figure 5.15. and its use is as follows: before performance of cost calculations, information about network – power lines' lengths and other corresponding technical parameters has to be gathered. Once the information is gathered, the process is followed by gathering information about available power line costs and statistics of power line faults. Cost estimation begins with a choice – to take or not to take credit for network development project. In case of taking credit, calculations have to be performed using NPV method, therefore such parameters like bank interest rate, inflation and credit period have to be defined. Taking into account different cable line and overhead line maintenance and fault elimination practices, costs of these activities are carried out using different mathematical expressions – ones for cable lines, and another – for overhead lines. Final result is obtained using (5.3). Numbers in brackets that are mentioned in the algorithm correspond to the numbers of equations in the thesis.

Power line construction costs per year of operation can be assessed using equation (5.4) that is based on NPV method.

$$C_i = \frac{C_{1kmi} \cdot l_i \cdot \left(1 + \frac{\mathrm{int}_r}{100}\right)^{t_{cr}}}{\left(1 + \frac{\mathrm{inf}}{100}\right)^{t_{cr}} \cdot t_{ei}} \tag{5.4}$$

where

C_{1kmi} – construction costs of lines with parameters i [monetary units / km];

l_i – length of lines with parameters i [km];

int_r – interest rate [%];

inf – inflation [%];

t_{ei} – operation time of lines (life time) with parameters i [years];

t_{cr} – time of credit [years].

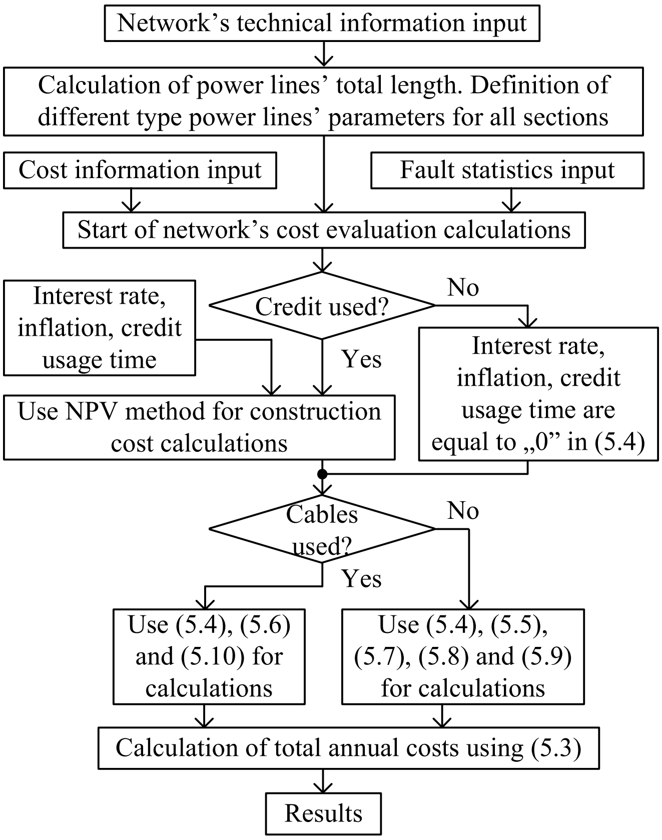


Fig. 5.15. Algorithm for system operator cost assessment

Calculation of preventive repair/maintenance costs should be calculated separately for overhead and cable lines because of differences in maintenance works performed. Equation (5.5) is proposed for preventive repair/ maintenance costs evaluation of overhead lines, but (5.6) – for cable lines.

$$C_{mi} = N_i \cdot (C_{org} + C_{op.s} + C_m) \cdot \frac{l_i}{100} + l_i \cdot 1000 \cdot l_{pzi} \cdot C_{cpz} \cdot \frac{1}{p_{cp2}} \tag{5.5}$$

$$C_{mi} = \frac{l_i \cdot 1000 \cdot l_{pz.i} \cdot C_{cpz}}{p_{cpz}} \tag{5.6}$$

where

N_i – number of preventive repair works during 1 year [monetary units/(km*year)];
C_{org} – work organizing costs [monetary unit/preventive repair work];
$C_{op.s}$ – costs of operative switching [monetary unit/switching];
C_m – costs of materials used during one preventive repair [monetary units /repair];
$l_{pz.i}$ – total protective zone length (to both sides of line) of lines with parameters i (for OHL up to 20kV is 2x6.5=13m; for cable line 2x1=2m – according to [40]) [m];
C_{cpz} – protective zone maintenance costs [monetary unit/m2];
p_{cpz} – time interval between protective zone maintenance works [years].

As in case of maintenance costs, fault elimination costs are calculated separately for overhead and cable lines. In case of overhead line, fault elimination costs are being performed for three specific cases:

1. Only wires are damaged;

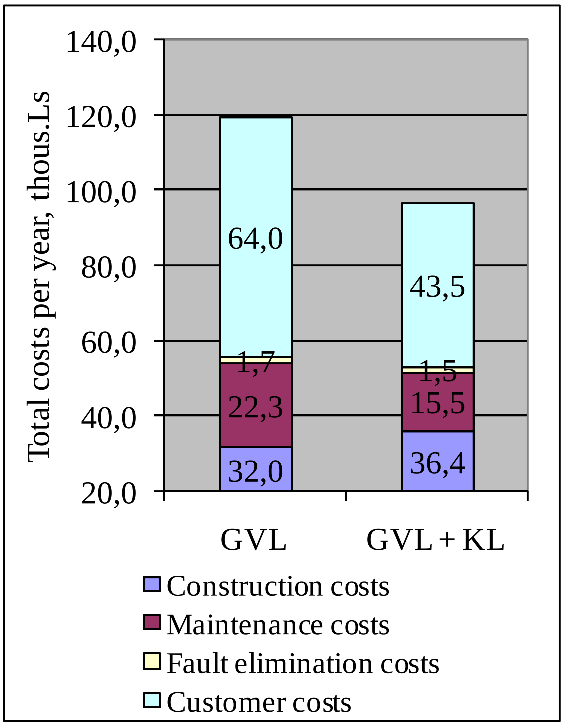
2. Line has damaged wires, isolators at two closest poles to the fault place are damaged, as well as two closest poles to the fault place are sloped down.
3. Line has damaged wires, as well as fully damaged two closest poles to the fault place.

In calculations of fault elimination costs detailed data about costs of fault elimination activities, such as trench digging costs, bond profile costs, earth surface restoration costs, etc. Equations for fault elimination costs of cable and overhead lines are not included in the summary due to space constraints.

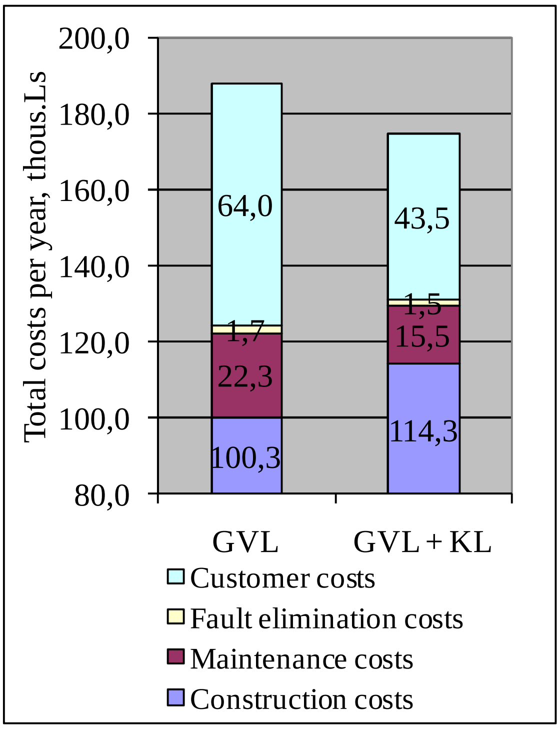
Results of calculations

Results of calculations of both customer and system operator costs are given in figure 5.16. Volume of customer costs is calculated on the basis of number of power supply interruptions and their duration.

At the figure 5.16. one can see changes of system operator and customer costs volume depending on the type of power lines used in the network. Abbreviation GVL corresponds to network that is formed by overhead lines, while abbreviation GVL+KL corresponds to situation, when feeder sections L1 and L2, as well as corresponding branches are overhead lines, but section L3 with the branches are cable lines.



a)



b)

Fig. 5.16. Distribution system operator and customer costs. Network is developed: a) without credit; b) taking credit in bank

Calculation results showed that optimal power supply reliability level cannot be chosen looking only from system operator perspective, because in case of cable line usage in the network, system operator costs in the best situation don’t change, but most probably will increase, that in its turn will result in need to increase network tariff. But assessing changes of customer costs depending on used power line type, it can be seen that usage of overhead and cable line combination gives positive effect and allows to decrease total costs.

6. METHODOLOGY FOR POWER SUPPLY RELIABILITY LEVEL PERFORMANCE-BASED REGULATION

In this section methodology for DSO power supply reliability level performance-based regulation is proposed. The proposed methodology is based on the author's studies and research that are described in the thesis.

In order to achieve optimal reliability level different power supply reliability level change options, that can both improve or decrease reliability, have to be compared. This will make it possible to determine target values of power supply reliability indexes. Therefore, it is necessary to carry out several activities, as reflected in the flowchart at figure 6.2. (activities with numbers).

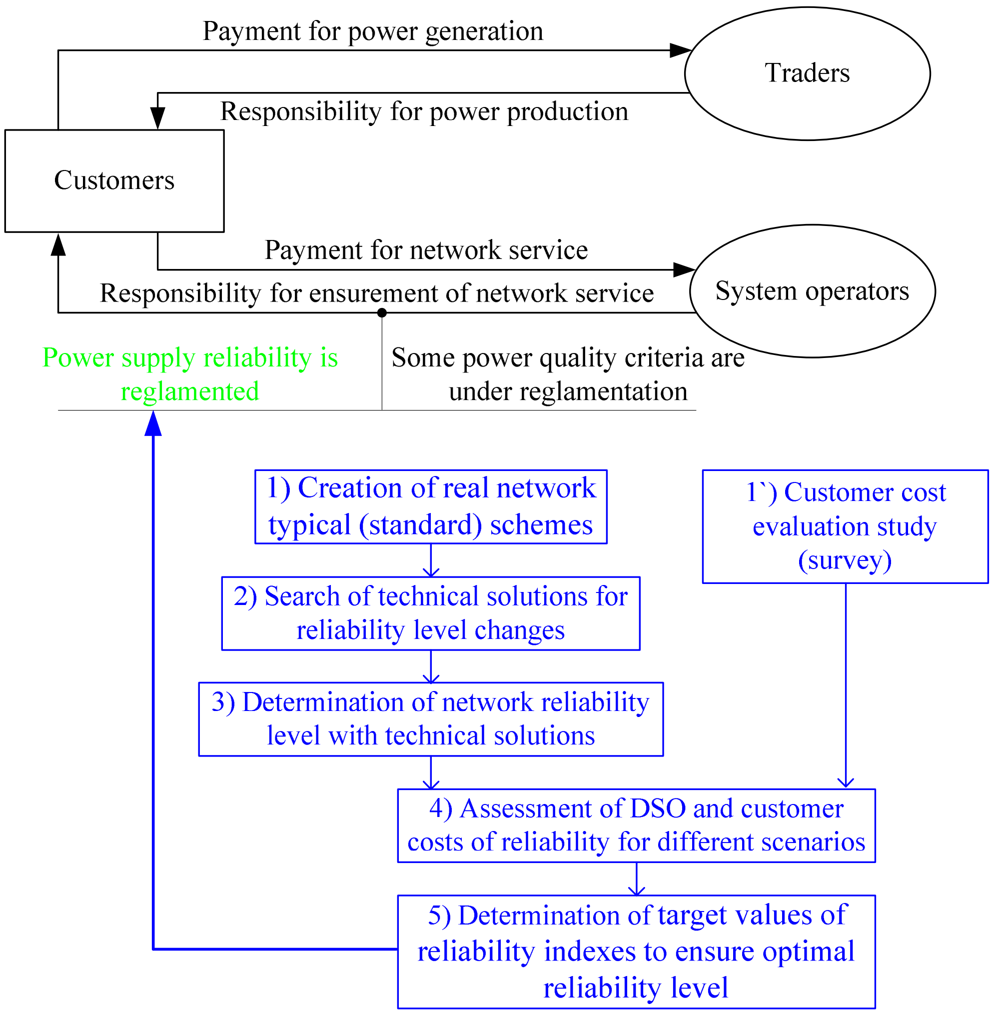


Fig. 6.2. Determination of power supply reliability indexes' target values as reglamentation of power supply reliability

As is clear from the proposed diagram, the primary activities of regulation implementation are: creation of network typical (standard) schemes and carrying out of customer cost evaluation study (survey).

Network typical schemes should as closely as possible reflect real network structure, as well as reliability level index values of typical network have to correspond to reliability level index values that are obtained from real network. Taking into account that in different country regions power networks have different structure, different typical network schemes have to be developed for precise network reflection.

Customer cost evaluation study (survey) should also be carried out with some time reserve before regulation introduction, because of big time consumption of study. In Latvian case, for information actualization new cost estimation study can be based on the study performed in the frames of this thesis.

After creation of typical network scheme, DSO should evaluate possibilities of introduction of different technical solutions for power supply reliability changes. Assessment of the technical options' affect on network reliability, as well as on DSO and customer costs is included in the points 3 and 4 of the flowchart (see figure 6.2.).

At the last, fifth, step target values of reliability indexes, that ensure optimal reliability level, are determined for planned and unplanned power supply interruptions. Besides SAIDI and SAIFI indexes, regulation of DSO should include CAIDI and MAIFI indexes.

In case if DSO don't achieve reliability target values within the regulation period, corresponding economical effect of unachieved target values has to be taken into account when defining DSO tariffs for the next regulatory period. In order to avoid too large differences between the power supply reliability level in the borders of one region, in the regulation there can be implemented not only DSO tariff adjustment depending on the reaching/not reaching reliability level targets, but also direct compensations to users (in cash or as a discount on the tariff) when power supply reliability level is worse than reliability target values 1.5, 2, or more times. In case if individual compensations are used it should be taken into account when defining DSO tariffs for the next regulatory period.

National regulatory authority and DSO have to cooperate closely when developing network typical schemes and when defining reliability assessment methodic, as well as methodic for customer and DSO reliability related costs volume estimation. Taking into account the fact that changes in network take several years, regulatory periods should also have comparable lengths. Appropriate period for regulation can be 3 years. Together with reliability objectives, national regulatory authority approves adequate distribution tariff, that would allow DSO achieve defined reliability goals.

Methodology for achieving optimal reliability level that is described above includes usage of power system reliability indexes and customer monetary costs. However for some electricity customer groups, particularly households, negative effect of power supply interruptions is difficult to be expressed in terms of money, as monetary losses due to power supply interruptions are minimal or don`t exist. In such situation optimal power supply reliability level can be very low – it would allow a large number of interruptions with long durations. But such situation endangers the safety and economic development in general. In this situation it is crucial to the ministry responsible for energy field to define the minimum power supply reliability criteria, taking into account not only economic, but also social safety criteria. This means that part of DSO tariff will not depend on users' monetary losses (costs) and, consequently, will not impact tariff changes associated with the optimal power supply reliability level.

Taking into account the fact that some groups of customers experience much bigger negative effect of interruptions, it would be worth to consider the possibility of establishing a distribution network areas of guaranteed or just higher than average level of power supply reliability, e.g. for industrial customers.

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

Analysis of existing situation showed that in Latvia, especially in rural areas, level of power supply reliability is one of the worst in Europe. Differences in values of reliability indexes depend not only on different network structure and geographical location, but also on non-uniform methods used for determination of power supply reliability indexes.

Performed analysis of existing performance-based approaches that are in use abroad, showed that used approaches cannot ensure optimal power supply reliability level, as the target values of network reliability are usually based on reliability level of neighboring countries or taking into account some average historical level of power supply reliability. Also not at all countries study on customer costs of reliability have been performed.

Performing analysis of network reliability indexes, there have been defined indexes that should be used in regulation, as well as identified shortcomings of the methods used for classification of indexes. On the basis of analysis in the thesis there is offered new approach for classification of reliability indexes, as well as indexes that would be applicable in regulation.

Questionnaire, that is based on the most effective methods for cost estimation, have been developed for customer costs of reliability estimation. The proposed questionnaire has been tested at the customer cost estimation study carried out in the frames of the thesis. Customer cost data have been obtained using e-mail - by sending questionnaires to 3000 customers. Analysis of received and processed results showed their high plausibility and confirmed that number of respondents for the study have been chosen correctly. The study and developed questionnaire can serve as the basis for further studies to update obtained results, as well as for introduction of performance-based regulation in Latvia.

Methods for estimation of reliability parameters have been analyzed in the thesis.

Different power supply reliability improvement technical solutions for distribution network have been studied and evaluated. Algorithm for estimation customer costs of reliability, that takes into account time-variable load and outage costs, have been developed. Algorithm for calculation of DSO costs related to reliability have been developed too.

In the thesis there have been performed in-depth analysis of one of technical solutions – partial replacement of medium voltage overhead power lines by underground cable lines. Aforementioned algorithms have been tested using the example and real data about network, customers and DSO. Calculations have been performed for typical rural network scheme that is based on available information about network. Time-variable customer costs that have been obtained in the Latvian customer study, as well as time-variable loads have been used in the in-depth analysis. The results of the calculations showed technical and economical benefits of cables, as well their ability to contribute to the optimal power supply reliability level in Latvian conditions.

On the basis of performed research, analyses, and developed algorithms, performance-based regulation methodology of power supply reliability level have been proposed. Taking into account that usage of the proposed methodology foresees finding optimal reliability level, as well as stimulating DSOs to achieve such level of reliability, the proposed methodology could help to improve public welfare. Introduction of the regulation methodology into practice will not only define real responsibility of DSO for reliability, but also help to clearly identify and justify further development of distribution network. The fact will help to improve the investment environment in the country, as new businesses will have access to clear information about power supply reliability of the state and its future developments.

The developed and proposed methodology eliminates the existing regulatory gaps and expects strong involvement of DSO and national regulatory authority in reliability level regulation. Consequently, the objective and tasks of the thesis are met.

When working on the practical implementation of the regulation methodology it is recommended to perform in-depth analysis of power networks to define regions with similar and different network and customer structure, as well as to develop typical network schemes for defined regions.

To forecast changes of network reliability level due to implementation of technical solutions, DSO should work harder on creation of more detailed statistical base, which would include information about the faults of network elements and their causes.

Despite the fact that there have already been performed customer cost estimation study for Latvian customers, such studies have to be also performed in the future. It would be also desirable to use other survey conduction methods, as well as perform to a particular customer sectors oriented surveys, which will further increase plausibility and accuracy of the results.

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