RIGA TECHNICAL UNIVERSITY

Faculty of Power and Electrical Engineering
Institute of Power Engineering

Nauris JANKOVSKIS
Doctoral student of the Power and Electrical Engineering (study direction: Power Engineering) doctoral study programme

TECHNIQUES OF USING SMART TECHNOLOGIES IN THE DISTRIBUTION NETWORKS OF LATVIA

Summary of the Doctoral Thesis

Scientific Supervisor
Dr. habil. sc. ing., Professor
A. S. SAUHATS

Scientific Consultant
Dr. sc. ing., Senior Lecturer
S. BERJOZKINA

RTU Press
Riga 2016

Jankovskis N. Techniques of Using Smart Technologies in the Distribution Networks of Latvia. Summary of the Doctoral Thesis. – Rīga: RTU Press, 2016. – 33 p.

Printed in accordance with decision No. 31/16 of RTU Doctoral Board P-05 (Power and Electrical Engineering) dated 10 October 2016.

The obtained results have been reflected in the project "Innovative energy resource extraction and utilization technologies and provision of low carbon emissions with renewable energy resources; support measures for limiting environment and climate degradation – LATENERGI" of the State research programme and in "Arrowhead", an international programme project.

ISBN 978-9934-10-872-3

DOCTORAL THESIS
PROPOSED TO RIGA TECHNICAL UNIVERSITY
FOR THE PPROMOTION TO THE SCIENTIFIC DEGREE
OF A DOCTOR OF ENGINEERING SCIENCES

To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotional Council on November 24, 2016, at the Faculty of Power and Electrical Engineering Riga Technical University, 12 k-1 Āzenes iela, auditorium 306.

OFFICIAL REVIEWERS

Assoc. Professor, *Dr. sc. ing.* Anna Mutule,
Riga Technical University

Dr. sc. ing., Senior Engineer of the Development Department
of JSC "Sadales Tīkls"
Aleksandrs Gavrilovs,

Assoc. Professor, *Dr. sc. ing.* Audrius Senulis
University of Klaipeda, Lithuania

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 Sciences 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 other scientific degree.

Nauris Jankovskis ……………………………. (signature)

Date ………………………

The Doctoral Thesis has been written in the Latvian language and consists of an introduction, 6 chapters, conclusions, a bibliography with 110 sources of literature, and 76 figures and illustrations. The total volume of the Thesis is 165 pages.

Table of Contents

1. INTRODUCTION

1.1. The topicality of the subject

The high prices of energy, the impact on the environment and climate, power cuts, and the related economic and social losses, as well as the limited nature of the known fuel have given grounds for acute attention of society towards the process of power supply [1]–[3]. New or modernised technologies are proposed and implemented (renewable energy resources, distributed generation, combined heat and power generation, energy storage, etc. [4]–[6]). Over the recent years, *using smart technologies in power networks* has become one of the most widely studied power supply development directions [7]–[9]. International conferences are held and significant investments are allotted for research. Still, for the time being, there are relatively few studies that show the real or potential gains in numerical form. It has been pointed out that the efficiency of new technologies considerably depends on the exact conditions and varies even within one country. The task has not been formulated and solved in this form for the conditions of Latvia, either.

Summarising the information in a number of studies [10] and knowing that there is no unified and confirmed definition of *smart grids*, let us adopt the following definition: *A power system network, which provides energy to a large number of customers and is equipped with intelligent communication infrastructure for stable, reliable and efficient supply of energy.* The marked words are to be considered keywords.

It can be expected that the following main tasks will be solved by the smart technologies:

1) diminishing of energy losses, which in turn will diminish the amount of emissions and the energy prices;
2) smoothing out of the energy consumption graph. The costs required for maintaining the reserve will diminish, as will the energy prices, accordingly;
3) an increase in the share of renewable energy resources, leading to a decrease in the amount of emissions and possibly the price;
4) an increase in the reliability level and, correspondingly, diminished duration of power outages, arranging “island modes”, diminishing of the dependence on high-voltage networks.

In order to achieve the above goals, technologies that can be used with communication network, including the Internet, are analysed and proposed.

Smart grids use such innovative technologies as:

1) modern metering infrastructure;
2) distributed generation technologies, which make it possible to integrate a large number of distributed generators in the distribution network (DN);
3) electric transport charging infrastructure, which aids wider spread of electric cars;
4) grid automation equipment.

The creation of new power networks as well as the expansion or reconstruction of the existing ones requires considerable material, financial and labour resources. These are needed for the construction works related to electrical equipment, assembly and installation works, and other types of works. Therefore, it is necessary to conduct technical and economical assessment calculations, determining the proportions of means for the construction of new energy facilities and for the reconstruction of the existing ones.

Optimal development of networks requires in-depth scientific research by using the methods of systems analysis, taking into account the dynamics of the changes in the equipment characteristics and the increase of the consumers' loads for the whole power supply system [11]–[13].

This Doctoral Thesis is dedicated to the solution of separate tasks related to a rational set-up of power supply systems based on the example of Latvia. All the above aspects and the topicality of their discussion have determined the choice of the subject and the goals and contents of this Doctoral Thesis.

1.2. The goal and the tasks solved by the Thesis

The goal of the paper is, by using the opportunities offered by smart grids, to contribute to economically efficient operation and development of the power system. The paper aims at facilitating the distribution network designing, construction and operation solutions.

To achieve the set goal, the paper dealt with the following **main tasks**:

1) to conduct an analysis of the condition and technologies of smart grids and Latvia's distribution networks was conducted;
2) to substantiate the need to use the stochastic approach in distribution network development planning tasks was substantiated;
3) to create a library of the load processes of electric energy users (EEUs);
4) to synthesize the distribution network optimization models.

1.3. Research methods and means

1. In the theoretical chapters, the methods of mathematical statistics [14]–[15] and the *Monte-Carlo* method (MCM) [16]–[17] were used.
2. To solve the tasks of the Thesis, the power system process simulation software *ETAP* [18] and the *MATLAB* programming environment [19] were used.
3. For the research, a specialised distribution network simulation software was created for choosing electric line parameters, which addressed the following problems:
   3.1. the developed algorithm takes into account the stochastic nature of energy price, ambient temperature and loading;
   3.2. the proposed algorithm allows finding the minimum annual operation and construction costs and helps to choose the optimal conductor cross-section;
   3.3. by means of the program, the variable parameters can be quickly changed and recalculated according to the set data.
4. The process library has been placed into a database of a national-scale research centre.
5. The parameters of the power transmission lines were calculated by using a specialised software complex, *PLS-CADD* [20], which enabled the author to examine and choose the power transmission line design alternatives with the lowest costs, taking into account the existing technical limitations.

1.4. The scientific novelty of the Thesis

1. The data of the operation indicators of the distribution network of the Latvian power system have been summarized.

2. A new approach for designing rural networks has been developed.
3. The possibility of using distributed generators for voltage regulation has been substantiated.
4. The rationality of using simplified substations (SSs) with high-speed communication channels in rural areas has been suggested and substantiated.
5. An automation device for relay-based protection devices (RPDs) and communication channels (a patent has been obtained).
6. A library (database) of the processes influencing the distribution network has been created, which can be used for solving many scientific and designing tasks.

1.5. The practical implementation of the Thesis

The practical significance of the doctoral paper is expressed in the following:

1) the proposed new distribution network designing methodology and the developed software can be used by many design companies in Latvia and the Baltic states;
2) the economic evaluation of SSs allows, in many cases, choosing the proposed alternative and saving hundreds of thousands of euros per facility;
3) the practical significance of the algorithms and methodology proposed in the paper:
   - in theoretical and scientific studies related to rational construction of power supply systems and optimisation of the technical parameters,
   - at energy companies which are active in the development and designing of power supply layouts;
   - the employees of the distribution grid operator's (DGO) development and operation department/functions, taking into account the proposed alternatives for implementing the connection of SSs;
4) designing of new 330–110/20 kV SSs, using technical and economic aspects.

1.6. The author's personal contribution in the research performed

The foundation of the basic theses to be defended consists of ideas created in close co-operation with the scientific supervisor of the paper, Professor Antans Sauhats, as well as with Dr. sc. ing. Svetlana Berjozkina and Dr. sc. ing. Ļubova Petričenko. This Doctoral paper can be partly regarded as the continuation of a long-time work of the Professor. The checking of the ideas, the models, the synthesized software, the numerical experiments and their analysis as well as the recommendations for efficient application belong personally to the author.

1.7. The approbation of the Thesis

1. Participation in the development of projects:
   1.1. the obtained results have been reflected in the project "Innovative energy resource extraction and utilization technologies and provision of low carbon emissions with renewable energy resources; support measures for limiting environment and climate degradation – LATENERGI" of the State research programme;
   1.2. the obtained results will be reflected in "Arrowhead", an international programme project.

2. Participation in patent development:

participation in the invention „Electrical grid relay-based protection device and method”, number P-16-52 assigned on June 29, 2016. A. Sauhats, D. Antonovs, M. Kuņickis, N. Jankovskis.

3. The results of this Doctoral Thesis have been reported and have received positive evaluation at six international conferences:
   3.1. 16th IEEE International Conference on Environment and Electrical Engineering, Italy, Florence, June 7–10, 2016;
   3.2. 13th International Conference on the European Energy Market EEM16, Portugal, Porto, June 6–9, 2016;
   3.3. 12th International Conference on the European Energy Market EEM15, Portugal, Lisbon, May 19–22, 2015;
   3.4. 5th International Conference on Power Engineering, Energy and Electrical drives POWERENG 2015, Latvia, Riga, May 11–13, 2015;
   3.5. 55th International Scientific Conference on Power and Electrical Engineering of Riga Technical University RTUCON 2014, Latvia, Riga, October 14, 2014;
   3.6. 4th International Symposium on Environmental Biotechnology and Engineering, México, Mexico, September 9–12, 2014.

1.8. Publications

The results of the paper are reflected in <u>internationally reviewed collections of scientific articles</u>:

1. Berjozkina S., **Jankovskis N.**, Sauhats A. Cost-benefit analysis of simplified substations // Proceedings of the 16th IEEE International Conference on Environment and Electrical Engineering, – Florence, Italy: IEEE, 2016. – p. 6 *(to be published)*;
2. Petričenko Ļ., Sauhats A., Berjozkina S., **Jankovskis N.** Stochastic Planning of Distribution Lines // Proceedings of the 13th International Conference on the European Energy Market (EEM 2016). – Porto, Portugal: IEEE, 2016. – p. 5 *(to be published)*;
3. Berjozkina S., Petričenko Ļ., Sauhats A., **Jankovskis N.** Overhead Power Line Design in Market Conditions // Proceedings of the 5th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG 2015). – Riga, Latvia: IEEE, 2015. – p. 5;
4. Berjozkina S., Petričenko Ļ., Sauhats A., **Jankovskis N.**, Neimane V. A Stochastic Approach to the Feasibility Study for Overhead Power Lines // Proceedings of the 12th International Conference on the European Energy Market (EEM 2015). – Lisbon, Portugal: IEEE, 2015. – p. 5;
5. **Jankovskis N**., Petričenko Ļ., Guseva S. Load Density Formation in Largest Cities // Electronic Proceedings of the 55th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2014). – Riga, Latvia: RTU, 2014. – p. 163–166;
6. Varfolomejeva R., Sauhats A., Petričenko R., Kucajevs J., **Jankovskis N**. Stochastic Approach to Economical Analysis of Biomass Power Plants // Abstract Book and Proceedings of the 4th International Symposium on Environmental Biotechnology and Engineering: Vol. 1. – México, Mexico: 4ISEBE, 2014. – p. 12.

1.9. The scope of the Thesis

The present Doctoral Thesis has been written in Latvian, consists of an introduction, six chapters, conclusions, a bibliography, 76 figures and illustrations, 165 pages all in all. The bibliography consists of 110 items.

2. THE READINESS OF LATVIA'S RURAL DISTRIBUTION NETWORKS FOR SMART TECHNOLOGIES

The second chapter analyses the readiness of Latvia's rural regions for smart technologies. The current condition of the distribution network and its development prospects are described; new or modernised technologies are proposed and implemented in practice (renewable energy resources, distributed generation, combined heat and power generation, energy storage, etc. [4]–[6]). It is pointed out that the efficiency of the new technologies greatly depends on the actual conditions and varies even within one and the same country. The task of evaluating the efficiency of the new technologies has not been formulated and solved with the conditions of Latvia in mind.

It has been concluded that the total length of the medium-voltage and low-voltage networks of the Baltic states and Latvia amounts to hundreds of thousands of kilometres. In these networks, significant energy losses are observed (5.9 % in 2012); these networks require considerable resources for operation, repairs and renovation [21].

Long-term development plans are being developed for the medium-voltage power network; in accordance with these, the power network in a settlement will be renovated or the reliability of power supply will be improved.

A review of smart technologies has been done, a definition of smart grids has been proposed; the expected advantages and available technologies have been reviewed.

Since recently, significant political stimulation of innovation in the energy sector has been observed in Latvia. The principles of introducing new technologies are taken from the EU directives. The following long-term strategic goals are stressed as the basis:

- increasing energy efficiency;
- environment safety;
- sustainability of resource utilization.

In order to reach these goals, it is necessary to work towards an increase in the energy efficiency of non-traditional and renewable energy sources. As regards technological improvement in Latvia, in order to increase the reliability and swiftness of action, the SCADA centralised system is used, which can improve the efficiency of control centres.

At the moment, Latvia is at the very beginning of the way towards the introduction of smart grids. The first steps towards smart grids were made when the JSC "Latvenergo" introduced AEUS — an automated electric energy metering system. True, this cannot yet be considered a modern metering system (MMS) since the electronic meters used do not ensure two-way communication and metering of the power flow in both directions; that is, they only store information regarding the hourly electricity consumption and data regarding de-energization and meter faults as well as submit the information to the system once every 24 hours [22]–[23].

The second chapter is concluded with an enumeration of the expected positive changes. Among them, the following ones can be mentioned:

1) diminishing of energy losses, which in turn will diminish the amount of emissions and the energy prices;
2) smoothing out of the energy consumption graph. The costs required for maintaining the reserve will diminish, as will the energy prices, consequently;
3) an increase in the share of renewable energy resources; consequently, a decrease in the amount of emissions and, possibly, the prices;
4) an increase in the reliability level and, consequently, a decrease in the duration of power supply interruptions, creating "island modes"; diminishing of the dependence on high-voltage networks.

3. POWERSYSTEM PLANNING TECHNIQUES THEORETICAL BACKGROUND

Chapter 3 is dedicated to a review and substantiation of power system planning methods. To solve development tasks of cities and city districts, it is necessary to rationally choose the parameters of the power supply system elements. To determine the design loads of cities or city districts, only orientative, generalized indicators and methods can be used. The paper reviews, analyses and compares two methods: the deterministic method, and the proposed stochastic approach to the forecasting and evaluation of city load; also, a stochastic approach for rational choice of network elements is proposed.

The deterministic method uses as the main input parameters the specific design load (per person) in the city residential sector and the number of inhabitants in the city, its residential areas, boroughs, blocks, etc. [24].

The tentative design load of a city residential area (borough, etc.) is calculated as follows [24]:

$$P_d = pl \cdot N_{ii}, \tag{3.1}$$

where p_l stands for the specific design load (per person) in the residential sector, kW/person; N_i — the number of inhabitants in a borough or residential area (persons). The average size of a household in Riga is 2.24 persons [25].

Given the specific design loads in the residential sector p_{sl} and the number of inhabitants N_i, based on (3.1), it is possible to calculate the design load P_d of residential areas (boroughs, blocks, etc.) for any prospective year, including, for example, the year 2020.

The total loading of the consumers should be balanced by a sufficient capacity of transformer substations (hereafter, TSs), taking into account the required reserve. The total estimated electric load of the city and a city district, considering the voltage level, can be expressed in general form as follows [24]:

$$S_{city} = k_{cc,j} \cdot \sum_{n=1}^{n_{TS}} S_{TS,i} = \sigma \cdot \Pi_{city}, \tag{3.2}$$

where $S_{TS,i}$ is the loading of the i-th transformer substation $i = 1, 2, \ldots, n_{TS}$, $k_{cc,j}$ — the randomness ratio of TS maximum loading energy system depending on the number of TSs in the network at the given voltage level j, $j = 0, 1, 2, \ldots, J$; n_{TS} stands for the number of transformer substations in the city under design; σ stands for the average load density for the city, MVA/km^2; Π_{city} is the total service area, km^2.

The aggregate load of the city can be determined as follows:

$$S_{city} = \sigma_a \cdot \Pi_{city} = \sigma_a \cdot \sum_{i=1}^{n_{TS}} \Pi_{TS,i} \quad , \tag{3.3}$$

where σ_a stands for the average load density in the city, MVA/km^2; Π_{city} — the built-up areas of the city and other related adjoining territory, km^2; $\Pi_{TS,i}$ — the service area of the i-th substation, km^2; n_{TS} — the number of transformer substations.

From the condition of equality, it follows that:

$$\sigma_a = \frac{k_{V,TS} \sum_{i=1}^{n_{TS}} S_{TS,i}}{\sum_{i=1}^{n_{TS}} \Pi_{TS,i}} = \frac{k_{V,TS} \sum_{i=1}^{n_{TS}} n_i \, \beta_i \, S_{nom,i}}{\sum_{i=1}^{n_{TS}} \Pi_{TS,i}} \quad , \tag{3.4}$$

where β_i stands for the loading ratio of the transformer of the i-th substation; $S_{TS,i}$ — the installed rated capacity of the i-th substation, MVA.

3.1. The deterministic approach to rational choice of network elements

Based on economic considerations, the choice can be made by the economic current density method or by the economic intervals method (EIM), which is based on the annual cost minimum criterion [26]–[33]. Taking into account the inaccuracies of the economic current density method, a fine-tuned EIM was created. The EIM implementation approach makes it possible to choose an economically substantiated, rational line conductor cross-section and ensure minimal total annual costs both regarding the construction of the power networks and their operation. The modification of this method is based on a search for the minimum of the total annual costs for electric line construction. As a result, calculations of economic intervals by current and capacity are conducted and their nomograms are constructed [26].

The total annual costs for each conductor cross-section depending on the current in the line can be calculated as follows [26]:

$$\begin{gathered} C_1 = (i + p_\Sigma)\mathrm{K}_{\mathrm{L}1} + 3\mathrm{I}_{\max}^2 \mathrm{R}_1(\tau\beta' + \beta'')10^{-3} \\ C_2 = (i + p_\Sigma)\mathrm{K}_{\mathrm{L}2} + 3\mathrm{I}_{\max}^2 \mathrm{R}_2(\tau\beta' + \beta'')10^{-3} \\ \ldots \\ C_i = (i + p_\Sigma)\mathrm{K}_{\mathrm{L}i} + 3\mathrm{I}_{\max}^2 \mathrm{R}_i(\tau\beta' + \beta'')10^{-3} \end{gathered} \tag{3.5}$$

where p_Σ stands for the total depreciation, maintenance and servicing deductions, r.v.; i — the interest rate, i.e. the bank loan interest, r.v.; K_L — the capital investments into power transmission lines (PTLs), €; $I_{\max}$ — the maximum line load current in the whole estimation period, A; R — the active resistance of the line conductor, Ω; $\tau = f(T_{\max})$ — the time of maximum losses, h; β' — the specific values of electricity losses, €/kWh; β'' — the price of capacity during the system load maximum, €/kW.

An optimal line alternative is characterised, firstly, by an economically useful cross-section of conductors that have been chosen for the implementation alternatives of a line of the specified voltage, for the specified values of the maximum capacity to be submitted, for the value of 1 kWh of lost energy, for the time of larger power losses, etc. The conductor cross-section, in the interval of which the capacity to be submitted is located, is economically useful [31]. Thus, this method allows constructing universal economic nomograms, which ensure convenient and more precise choice of the economic conductor cross-section of electric lines for various voltages and network designs [26], [33]–[34].

Notwithstanding the advantages of the EIM, it still does not fully function at the conditions of market economy. This means that at the present-day economic conditions, the traditional methods for choosing and determining the parameters of electric lines, for example, conductor cross-sections, need to be improved.

3.2. The stochastic approach to rational choice of network elements

The free market, the alternative and local sources of energy, new energy storage and communication technologies are those main factors, which, on the one hand, ensure alternative solutions for power system planning problems and, on the other hand, increase the level of uncertainty. The new conditions compel a search for and/or improvement of appropriate power system planning methods.

In order to check the validity of the deterministic approach in a stochastic environment, further on a stochastic approach for rational choice of electric line parameters is proposed. In the formulation of the optimization task under consideration, we will continue to preserve the essence of the objective function, i.e. we will strive to minimize the annual expenses. Furthermore, we will state that the expenses c in any time interval can be described by function φ as follows [35]:

$$c = \varphi\,(\,p_{sl}\,,\beta,\,t_{vid}\,,\Pi\,)\,, \tag{3.6}$$

where $p_{sl}\,,\beta,\,t_{vid}$ stand for line load, electricity price and outdoor air temperature, respectively; Π — other parameters that influence the annual costs c (the operation price, the credit amount and interest rate).

Analysing (3.6), we can state that load, price and temperature are random time functions. These functions are not stationary. Between them, correlative ties exist [36]. As a result, it is concluded that also c is a random time function since it is determined by corresponding random functions.

In order to describe a multi-dimensional random process $p_{sl}(t),\ \beta(t),\ t_{vid}(t)$, this process can be discretised in time, specifying the time moments. For each time moment, the probability distribution functions of the parameters $p_{sl}\,,\beta,\,t_{vid}$ need to be specified. These distribution functions can be described by distribution functions of the first, second, etc., orders according to [37]:

$$\left\{\begin{array}{c} \Phi_1(P_{\mathrm{sl}}^1,\beta^1,\mathrm{T}_{\mathrm{vid}}^1,t_1) \equiv P\{p_{\mathrm{sl}};\beta(t_1)<\mathrm{P}_{\mathrm{sl}}^1;\beta(t_1)<\beta^1;t_{\mathrm{vid}}(t_1)<\mathrm{T}_{\mathrm{vid}}^1\},\\ \Phi_1(P_{\mathrm{sl}}^1,\beta^1,\mathrm{T}_{\mathrm{vid}}^1,t_1;P_{\mathrm{sl}}^2,\beta^2,\mathrm{T}_{\mathrm{vid}}^2,t_2) \equiv\\ \equiv P\{p_{\mathrm{sl}};\beta(t_1)<\mathrm{P}_{\mathrm{sl}}^1;\beta(t_1)<\beta^1;t_{\mathrm{vid}}(t_1)<\mathrm{T}_{\mathrm{vid}}^1;(p_{\mathrm{sl}}(t_2)<\mathrm{P}_{\mathrm{sl}}^2;\beta(t_2)<\beta^2;t_{\mathrm{vid}}(t_2)<\mathrm{T}_{\mathrm{vid}}^2\\ \cdots \end{array}\right\}$$

,(3.7)

where P_{sl}, β , T_{vid} are the arguments of the distribution functions of the random variables p_{sl}, β, t_{vid} ; the superscripts correspond to the number of the discretization time moment; P — probability.

Given the function (3.6) and the probability distribution functions (3.7), the average value of the random process set of observations can be calculated [35]:

$$M[C_G] \equiv M[\varphi(p_{\mathrm{sl}}, \beta, t_{\mathrm{vid}}, \Pi)] = \\ = \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} \varphi(P_{\mathrm{sl}}^1, \beta^1, T_{\mathrm{vid}}^1; P_{\mathrm{sl}}^2, \beta^2, T_{\mathrm{vid}}^2; \dots) \mathrm{d}\Phi_n(P_{\mathrm{sl}}^1, \beta^1, T_{\mathrm{vid}}^1; \dots; P_{\mathrm{sl}}^n, \beta^n, T_{\mathrm{vid}}^n). \tag{3.8}$$

Analysing the expression (3.8), it can be easily concluded that the solution algorithm and the required calculations will become many times more complicated. Ample statistical data and labour-consuming calculations are required. Presumably, it is this phenomenon that has been the main inhibiting factor for using the stochastic approach. Due to the implementation of smart grid technologies, the above problem can be easily solved and multidimensional registration of parameters (capacity, outdoor air temperature, prices, etc.) and creation of an electronic database (library) are enabled. Thus, the above disadvantage of the stochastic approach becomes surmountable.

The concept of the stochastic approach consists of three main calculation stages:

1) forecasting the total design electric load of the city and city district under consideration, taking into account load increase scenarios as well as load planning and development aspects;
2) rational choice of the electric line parameters, mainly consisting in the choice of the optimal alternative of conductor cross-section with minimum total annual average costs (TAAC). Also, a detailed calculation of the capital costs of the electric lines is conducted, along with a calculation and evaluation of the power losses in the network. In the case of the distribution network, the conductor is additionally checked as to the permissible voltage losses;
3) calculation and analysis of the minimum TAAC as well as the net present value (NPV) of these for both of the discussed methods (the stochastic approach and the deterministic one) during the evaluation and planning period. Choosing a rationally substantiated design alternative.

Forecasting of future envisages forecasting of the load increase, taking into account the variable nature of the load. The load changes continuously and causes power losses in the network. The costs related to these losses depend on the electricity price. Besides, the electricity price varies as well. Also, outdoor air temperature needs to be considered as one of the forecast parameters due to its strong influence on power losses.

The list of design alternatives of the possible electric lines requires that the line design should be deliberated in several alternatives. The number of such alternatives can be enormous since various possible combinations of electric line parameters and designs exist. The choice of the appropriate combination depends on the voltage level of the electric line, the complexity of the line route layout and the length of the line as well as the choice of the main parameters of the line. To implement this step, it is useful and efficient to use powerful automated designing systems, for example, the PLS-CADD software [20]. Using the functionality of the PLS-CADD software [20], [37], a three-dimensional model of an overhead electric line (OEL) was developed, examining a number of alternatives of the model at different electric line operation modes and design conditions.

As a result of the above, the solution with the lowest capital costs is ensured and the enormous number of electric line design alternatives is at once diminished. Besides, it is necessary to take into account the electric line designing practice and experience, along with the observation of the existing technical limitations.

3.3. The creation of the process library

3.3.1. Introduction

The rapid development of information technologies clearly influences the development of smart technologies. It is possible to use the advantages offered by state-of-the-art data collection and summarization tools, such as the so-called smart meters. These meters make it possible to view the current consumption situation at any time period and in any consumption group of electric energy users, such as private houses, industry, various public buildings, etc.

The Thesis provides a method, according to which, when developing the design of a new village or town, a library of processes is taken as the basis, with typical electric energy user consumption load entities, also comprising air temperature and electricity price in a year-long perspective. Furthermore, when developing the design, it will also be possible to include the forecasting of prices in the future.

The first step when developing a design for the power supply of a new town is the development of a consistent and adequate preliminary design, comprising all the electric energy users and their expected load. The development of this preliminary design considerably influences the construction costs of the project since, as is already known, the construction of power supply networks is costly. Of course, it is also necessary to take into account that in the case of a positive net migration rate, the settlement will expand in the long run and additional capacity reserves will not be superfluous.

The paper presents the information collected regarding some city district loads and the methods of their calculation. The design load has been analysed and summarized by using foreign and Latvian literature sources and directive materials [28]–[29], [38].

3.3.2. Data collection and analysis

To perform the formulated task, a considerable amount of data was collected and processed. This is needed to ensure the geographical depiction of the city, including buildings and places, and the existing substations. A geographic information system (GIS) is one of the main sources of data. Also, *AutoCAD* drawings were made in order to reflect the required information. Besides, various information regarding the elements of the system was acquired manually. Data regarding the load of the existing distribution SSs is provided in *MS Excel* format. To obtain the graphs for the deterministic and stochastic methods, the data from smart electricity meters were also taken into account.

3.3.3. The process library

To collect data and create the processing library, the existing customer service and billing system (KANS) that is in place at the JSC “Latvenergo” was taken as the basis. In this complex database, each entity is grouped into categories and divided into consumption classes, which considerably facilitates work. Part of the functionality of the KANS database is related to its use for data collection and processing. In the creation of the library, several parameters were taken into account, which considerably influence the overall consumption and price picture of the electric energy user. An EEU is a natural or legal person, which purchases electricity for industrial and/or household needs.

The process library is based on the loadings of various groups of EEUs (multi-apartment residential houses, shops, hospitals and other public buildings, industrial buildings, office buildings, private houses, generation substations, etc.).

4. OPTIMIZATION OF ELECTRIC LINE PARAMETERS AT THE DESIGNING STAGE

Chapter 4 discusses examples of forecasting the load of cities and city districts, as well as examples of optimizing electric line parameters and the results of their examination. Upon comparing the above methods, the rationality of using the proposed stochastic approaches was substantiated. The above research results are based on the data of real-life substations and electric lines.

4.1. The "Zunda" and "Alūksne" projects

4.1.1. Introduction

Depiction of the actual loading picture of a power supply area is a very complicated process. Real-life data are used and all the factors influencing the load are taken into account — partial consumption by EEUs as compared to the demanded load, electricity prices, the planned repairs of the service area of the substation, emergency repairs, reconnections from/to other substations.

The above data make it possible to determine the electricity consumption of a transformer as well as the real-time load reserve. Yet, this does not show the loading data of the actual EEUs of the whole power supply service area, which would help to select the required and optimal capacity of the transformers and determine the loading of the PTLs in the city and/or city district in question.

4.1.2. The results of applying the methods and their analysis

The population of the service area of the **transformer substation "Zunda"** as of 2012 has been tentatively assumed to be 10 304 according to [39]. It has been assumed that the load in the residential and service sectors is about 80 % of the total load of the service area.

In order to check the appropriateness of deterministic methods in the stochastic environment, we will use the stochastic approach to power network load forecasting presented and proposed in the present Doctoral Thesis.

The results obtained by the reviewed methods are shown in Fig. 4.1.

Fig. 4.1. The loading of TS "Zunda" over the year by different methods.

By using the stochastic approach, we can see the periodicity of the load, which corresponds to seasonality. Outspoken load maxima (maximum grid loading) can be observed at electricity consumption peak hours as well as during the winter season.

As for the **substation "Alūksne"**, the bulk of its service area has been marked as a residential area; still, in this territory, there are many educational establishments and public buildings as well as a considerable industrial and commercial infrastructure. The actual service area of "Alūksne" consists of the southern districts. In 2010, the service area of the substation was approximately 1699.8 km^2.

A comparison of the results obtained by the reviewed methods is shown in Fig. 4.2. The loading tendencies persist similarly to the previous example, which means that the stochastic method can be used, for example, for a substation, a power transmission line, to determine the loading of the users, and it yields a realistic picture of the load changes in the grid at every hourly interval.

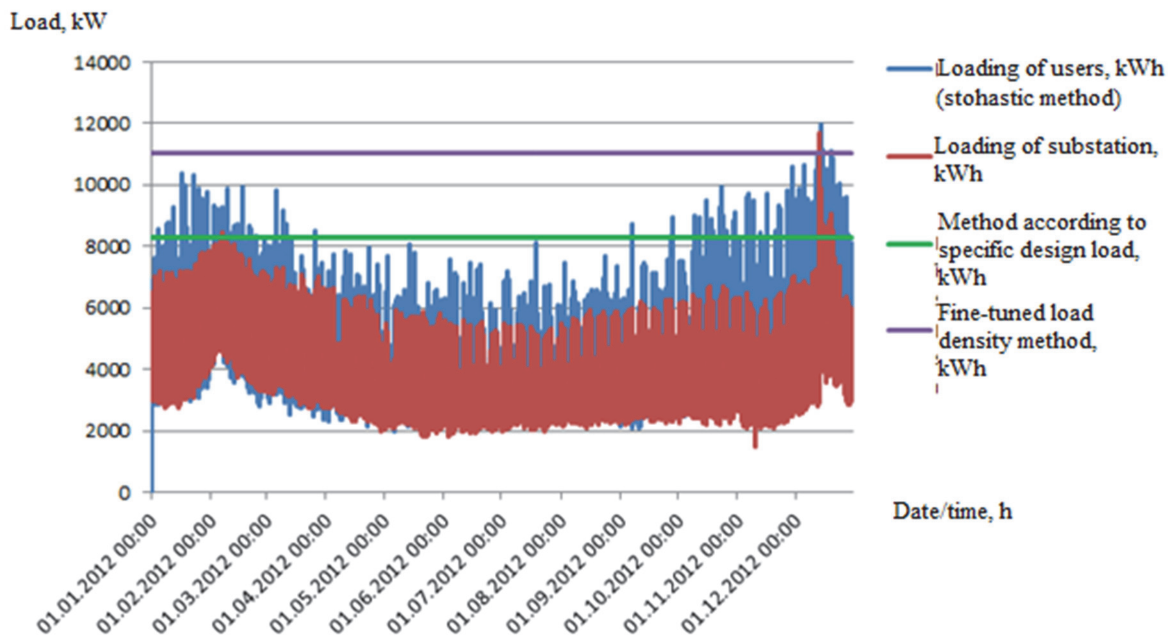

Fig. 4.2. The loading of TS "Alūksne" over the year by different methods.

The comparative analysis is based on the data of a design for the service area of the substation "Alūksne", which characterize the development of power supply to cities and towns. This design assumes that the capacity of the electric line increases by two per cent every year (the duration of one planning period is 30 years) [42].

Based on the obtained load graphs, the TAAC were calculated (for one year) for all the PTL design alternatives by using the exhaustive search method.

In our case, the above-mentioned program calculated the TAAC based on the 1st year of design implementation. Out of six line conductor cross-section alternatives, the first one (AS-50) has the lowest TAAC indicator. This means that the previously submitted graphs show all the possible TAAC values from the conductor cross-sections of the selected lines. As a result, the optimal TAAC value for AS-50 conductors has been determined as follows: in the first case (for transformer 1), the nominal TAAC value is 70 670 €; in the second case (for transformer 2), the nominal TAAC value is 98 750 €.

By using the above-described program, the NPV calculated from the TAAC is determined for each year over the whole PTL planning period. The obtained results and an analysis for both approaches are shown in Table 4.1.

Table 4.1

The results of the comparison between the deterministic method and the stochastic approach

	Stochastic approach	Deterministic method	Difference, %
TAAC, € (transformer 1)	2 127 316	2 938 016	38.10
TAAC, € (transformer 2)	2 969 634	3 614 564	21.71
NPV of TAAC, € (transformer 1)	1 573 659.14	1 960 109.09	24.55
NPV of TAAC, € (transformer 2)	2 216 492.09	2 518 936.5	13.64

Finally, it can be concluded that the proposed stochastic approach ensures considerable investment savings for all the design alternatives, which proves the substantiation and necessity of its use. Thus, it is necessary to take into account the electricity price and load fluctuations (the capability to meet the demand of the EEUs); this is particularly topical at market conditions.

5. SUBSTANTIATION OF THE CONSTRUCTION OF A SIMPLIFIED-LAYOUT 110-kV SUBSTATION WITH ONE TRANSFORMER

Chapter 5 provides a substantiation of the usefulness of constructing a 110-kVsubstation with one transformer.

5.1. Introduction

The increase in the power supply quality requirements and the unusual weather conditions that have been observed in Latvia over the recent years (for example, unusual changes in ambient air temperature, strong wind gusts, etc. [43]–[44]) represent a reason to review the architecture and topology of the distribution network. Besides, the development of the transmission and distribution networks and the management of new territories leads to the need to connect new loads and generators, which may be situated far from the existing substations, to the already constructed electrical networks.

At the places where the existing distribution network has not been constructed in such a way as to enable the connection of new capacities or increasing the permitted capacity of the existing consumer equipment, the following solutions are used at present:

1) reconstruction of the distribution network section in question;
2) construction of a new medium-voltage cable line (CL) from the buses of the substation, if the capacity of the transformer allows this;
3) construction of a new 110-kV substation, which would make it possible to diminish the number of those users that would be affected by the power supply disruption in case of medium-voltage network fault and during planned disconnections, increase the possibility of implementing new connections, diminish the power losses in the distribution network, and simplify the setting up of discriminative relay-based protection in the distribution network.

As a result of the restructuring of the power system, it can be concluded that the decision-making process regarding the choice of the electrical layout for substations will become more complicated, bringing about disagreement between system operators (SOs), which could be mitigated if the company in the more advantageous situation were to fully compensate the loser for the additional expenses incurred. However, on the whole it can be concluded that the end user of electricity will be the main winner in this situation. Summarization of experience leads to the emergence of standards and regulations, which in many cases considerably facilitate the decision-making. Yet, in many cases, if the conditions change, the amassed experience lacks validity since in the new situation, the power system development tasks need to be solved by considering new technologies and requirements as well as considerably improved equipment parameters (smart grids, communication channels, transformers, instrument transformers, communication switching devices, increasing of reliability, diminishing of losses, etc.).

Connection to the networks of the distribution system operator (DSO) may be accompanied by the need to construct long medium-voltage lines with considerable capital investments and servicing costs. In cases when the new loads and generators are situated relatively close to an existing high-voltage transmission line, it is possible to build a new substation. This way of setting up a connection is characterised by high costs as well. The costs can be diminished by choosing a rationally substantiated electrical layout for connecting the new electrical utilization equipment and generators. The possible ways of setting up the power supply connection are to build new additional 20-kV electric lines up to the place where the utilization equipment is connected or to build new substations. In this case, a decision has to be made as to whether to build expensive substations, for example, H-type substations, or simplified substations with one transformer, which are less expensive and, if correctly planned, they may considerably improve the reliability and quality of power supply for the end user. In all cases without exception, when providing the substations of the existing type with a H-type layout and place for two transformers, there is an artificial increase in the size of the installed capacity of the transformers; the resources of the SDO are blocked, awaiting the potential load increase; the connection setup costs for the users are groundlessly increased [45].

Block layouts most often find their application at simplified substations; here, two or more elements of the network, for example, a line and a step-down transformer ("L-T") (see Fig. 5.1), are connected in series and operate separately from other blocks. Therefore, in case of a fault or repairs at one of the elements, the second element of the unit is also disconnected.

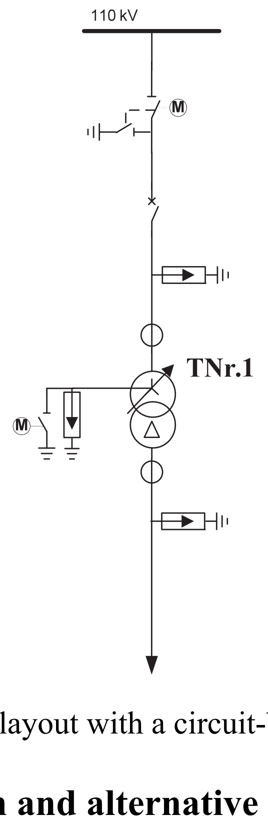

Fig. 5.1. A block layout with a circuit-breaker TNr.1.

5.2. The essence of the problem and alternative solutions

In order to explain the essence of the problem, let us look at the overall layout of the various alternatives of setting up a connection, which depicts the three reviewed ways of setting up a connection of a new utilization equipment and generators (see Fig. 5.2):

1) construction of a new additional 20-kV line (PL20) from the existing substation to the centre of electrical loads. In this case, the costs and the reliability depend on the

distance from the existing substations and the location and required capacity of the new utilization equipment and generators (the connection load). Each case has to be assessed individually;

2) construction of a H-type substation. This solution requires the largest amount of capital investments as compared with the other alternatives, which are substantiated by calculations that are provided below;
3) construction of a simplified substation. In all cases, this alternative requires less capital investments than the second one.

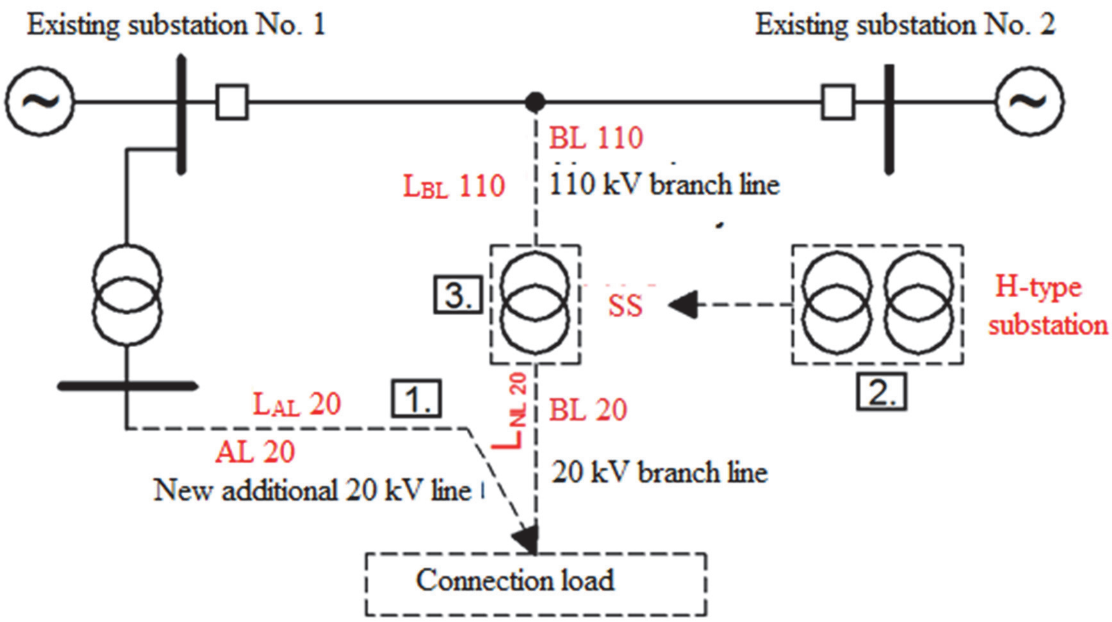

Fig. 5.2. The possible ways of setting up a power supply connection.

In comparison to the H-type layout, the use of simplified substations diminishes the power supply reliability level of a new connection at the following additional conditions: in case of high-voltage line fault, and/or in case of transformer fault and planned repairs.

5.3. The implementation of a simplified substation connection

The implementation of a simplified substation may have disadvantages of the following two types:

1) influence on the reliability of the network of the transmission system operator (TSO). This influence can be eliminated by using sufficiently reliable and fast communication channels and backing up the protection of transformer. The requirements set for the communication channels fully correspond to the modern-day possibilities, the concept of smart grids, and the reliability indicators already achieved (the availability factor exceeds 0.998);
2) a long-lasting power outage in case of faults of an unbacked-up SS transformer. In this case, the duration of the power outage is equal to the time required for replacing the transformer. The influence of this factor can be diminished to an acceptable level if:
   - the power system uses standard-type SSs;

- the power system holds reserve transformers in stock, which can quickly be used to replace the faulty ones.

Yet, the probability of these types of accidents is negligible due to the following reasons:

1) the experience of the last forty years shows that the faults of 110-kV transformers account for only about one per cent of all the power network faults, whereas the bulk of the faults are due to the faults of electric lines [46]–[47];
2) the service life of modern transformers is approximately forty years (for transformers manufactured according to the Russian State Standard (ГОСТ), the service life is ≥ 25 years); additionally, it is expected that more efficient transformer monitoring and troubleshooting systems will be developed and implemented, which will result in longer transformer service life and ensure the necessary level of reliability, by using a forecasting and technical condition management strategy [48];
3) in most cases, construction of a simplified substation is recommended if backup via the 20-kV network is ensured; yet, in such a case, there are also problems, for example, loss of voltage quality, increase in losses, etc. Yet, each case has to be assessed individually.

Upon evaluating the experience of foreign (German and other) power companies, it was found out that SSs are constructed as frame buildings or container-type substations with a high-voltage and medium-voltage gas-insulated switchgear, which considerably facilitates the construction and further operation of the substations [49]–[51].

At simplified substations that are built as frame buildings or container-type substations, German power companies widely use a medium-voltage gas-insulated switchgear. The bus current of the 20-kV switchgear $I_{bus} = 1250$ A, the current in the outgoing feeder $I_f = 630$ A. This means that for a standard 110/20-kV substation design, a transformer with a capacity of up to 40 MVA can be used. Considering the present load density and loading in Latvia's cities and regions, such a transformer capacity is topical only in large national-status cities and/or for future needs (prospective connections). Our suggestion is that simplified substations should be built as frame buildings or container-type substations, with a capacity of not more than $S_{rated} = 16$ MVA. Also, the capacity of the transformer depends on the ability of the existing medium-voltage power supply network to reserve the required capacity from adjacent substations. The number of outgoing feeders depends on the configuration of the network, the number of customers, and the load in the area in question. We suggest that the number of outgoing feeders should not exceed five electric lines. In a frame building or a container-type substation, ten cubicles can be placed: the connection of the transformer, the connection of the arc-suppression coil, the connection of the auxiliary transformer, and seven connections for outgoing feeders. We suggest that two auxiliary transformers should be installed: the transformer No. 1 should be connected to the 110/20-kV buses, and the transformer No. 2 should be connected to the 20-kV cubicle. In case of the loss of voltage at the 110-kV side, the auxiliary transformer No. 2 can be powered from the existing 20-kV network by using the backup possibilities. The capacity of the auxiliary transformer does not exceed $S_{rated} = 25$ kVA.

As a result, it can be concluded that it is planned that SSs will mainly be built in rural areas or/and in small towns; consequently, the SS can be designed by using an air-insulated switchgear (the lowest costs). As a future design, as the prices diminish, a frame building or a container-type substation with a medium-voltage gas-insulated switchgear would be a very suitable solution, since such a design has a number of advantages, for example, a small number of outputs (the total construction costs diminish), compactness (it is thus possible to foresee the space for prospective connections), a higher operation reliability; if necessary, a container-type substation can be easily moved to a different location, etc.

5.4. The operation and organization of relay-based protection in the case of a simplified substation

5.4.1. The influence of branch transformers on relay-based protection and automation

In Latvia, there are a number of SSs. The rule is one branch per line. One of the advantages in building a SS is the possibility to avoid building additional PTLs. The disadvantages are the decrease in PTL reliability and the increase in the degree of the complexity of the relay-based protection.

The number of rigidly connected branch substations (i.e. with a branch, not a power circuit-breaker) between the existing substations must not exceed three [52].

The SS "B" has no circuit-breaker at the high-voltage side (the TSO). The line No. 2 has protection only at the substations "A" and "C" (see Fig. 5.3).

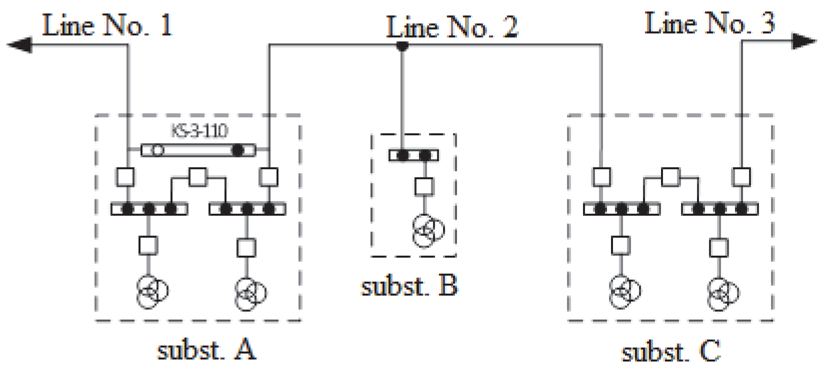

Fig. 5.3. Example of SS "B"; line No. 2 joins substations "A" and "C".

In the case of a short circuit on the buses of substation "B" (the high-voltage side — 110 kV), the distance protection (DP) of the first zone of the line No. 2 will come into action for substation "A" and substation "B".

In the case of a short circuit beyond the transformer of substation "B" (the medium-voltage side — 6, 10, or 20 kV), the protection of the transformer will come into action. Two protection sets are installed for the transformer, ensuring the near backup. A failure of the second protection set of the transformer is unlikely, therefore **the 110-kV line No. 2 is not provided with distance backup.**

<u>**Near backup** is understood as the use of two protection devices in a connection, which provide backup for each other, each of them with a sufficient sensitivity in the basic operation zone</u>, and they are usually based on different principles.

In the case of a fault, two protections operate for the transformers — gas protection and differential protection, by which the near backup of the protections is ensured (of course, the near backup is ensured only in the case of such faults when both protections have a sufficient sensitivity).

In the cases when near backup of the protections is ensured at a facility, simultaneous faults of both protections are unlikely and the need for corresponding connections of remote backup protections arises rarely.

In the case of a fault in the connection and a fault of the circuit-breaker, near backup cannot ensure the isolation of the fault. Therefore, the near backup means are complemented with special devices for backing up the circuit-breaker faults, which ensure the switching-off of the circuit-breakers that are nearest to the fault location in the mode under consideration.

The type of backup that is used for backing up the protection devices or the circuit-breakers of adjacent sectors **is called remote backup**. Such backup is performed by the protection (and the circuit-breaker is switched off) not at the facility where the fault has occurred but at other, remote substations.

Consequently, if there is a fault in a branch line (BL) following the fault of its protections or its circuit-breaker, the protections have to operate and the circuit-breakers and switches have to switch off at the substation "B" as the functions of the remote backup are performed.

Remote backup ensures the isolation of emergency places and stopping of the short-circuit current and the development of equipment damage.

To increase the sensitivity of protection devices, special protection sets are installed in the bus coupler circuit-breakers and switched busbar circuit-breakers for operation in the remote backup mode. If such a protection set allows switching off the bus coupler circuit-breaker, then one of the systems of the bus and with it a number of lines and a substation will be separated from the faulty system section. In connections that are connected to a different bus system with the faulty element not switched off, the short-circuit currents increase, the sensitivity of the protections, which ensures remote backup, increases.

In this way, the near backup of the transformer protection is performed in Latvia by means of a second protection set whereas remote backup cannot be ensured due to a number of reasons:

1) there are no normative requirements regarding the remote backup of transformer protection;
2) the technical limitations of the modern microprocessor terminals. There are limitations regarding resistance settings — up to 250 Ω. When short circuit emerges in the medium-voltage network of the simplified substation, it is not possible to ensure sensitivity. In this case, very small currents flow at the end of the 110-kV line, which means that the impedance up to the short circuit location is very high — considerably higher than 250 Ω (up to 600…700 Ω);
3) the near backup is reliable. The failure of the second protection set is unlikely;
4) at feeding substations, very often there is a bypass repair bus KS-3-100. In Latvia, there are very many substations of this type. Such a bus makes the installation of circuit-breaker failure automation more complicated.

5.4.2. Arrangement of relay-based protection

Modern-day technical means make it possible to conduct continuous monitoring of communication channels and recognize, practically at once, its faults. These possibilities can be used to eliminate all the negative effects of building a simplified substation for the transmission system operator. In the case of disturbed communication, it is sufficient to disconnect the simplified substation from the transmission network (TSO). The above measure can be convenient and acceptable if the reliability of the communication channels is high, and thus the pattern shown in Fig. 5.4 can be recommended for dealing with clashes of the interests of the transmission system operator and the distribution system operator.

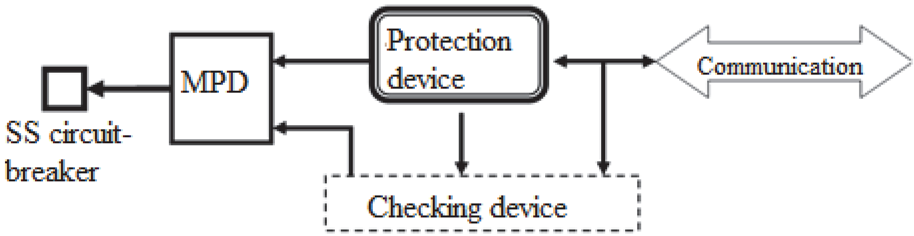

Fig. 5.4. Proposed basic layout for ensuring the operation of communication channels.

The essence of the proposed solution is as follows:

1) continuous monitoring of the communication channels is conducted;
2) the information exchange between the high-voltage line substations (the TSO) and the simplified substation is used. In the case of a fault in the high-voltage line, the circuit-breaker of the simplified substation is switched off. Such a solution eliminates the influence of the simplified substation on the operation of the power transmission line but only if the communication is viable;
3) the circuit-breaker of the simplified substation is also switched off in the case of communication channel faults.

Let us point out that the existing communication channels are reliable (their availability factor exceeds 0.998); however, they do not ensure a corresponding relay-based protection control algorithm for the case of communication channel failures. The above-explained solution ensures this, corresponds to the smart grid concept, is easy to back up, and is capable of eliminating the interest clashes between the distribution system operator and the transmission system operator.

5.5. The concept of the proposed alternative comparison method

As different alternatives are compared, it is necessary to select the indicators (criteria) for evaluating their efficiency. Considering that all the compared alternatives are capable of meeting the energy demand of the consumers, it can be assumed that the revenue from this service is equal in all the discussed cases. In this situation, the alternative that ensures the lowest design implementation and maintenance costs can be regarded as the most profitable one.

The proposed simplified substation protection approach (see Fig. 5.4) makes it possible to disregard the influence of constructing a simplified substation on the reliability of the existing 110-kV main electric line since it is proposed to apply a technical solution that foresees using a fast and reliable communication channel.

The costs that are determined according to the proposed method consist of three parts: construction costs, costs related to the losses of electric power, and costs related to undelivered electricity. The construction costs and the loss costs are attributed to the distribution system operator both as to the 110-kV voltage and the 20-kV voltage. When determining the costs to the distribution system operator, the costs related to the 20-kV circuit-breakers and the 20/0.4-kV transformers as well as the low-voltage electric lines are neglected since they remain unchanged for all the accepted alternatives.

The proposed method makes it possible to determine the total annual costs for each solution, so that the alternative with the lowest costs can be chosen.

5.6. Examples, obtained results and their analysis

In order to develop and substantiate the criteria for building simplified substations, the three above-mentioned alternative solutions need to be reviewed (see Fig. 5.2), varying the following main parameters: the length of the 110-kV branch line (BL 110), the length of the 20-kV branch line (BL 20) — the 20-kV line to be constructed from the SS to the electric loads centre; the length of the new additional 20-kV line (AL 20) to be constructed — the distance from the existing substation to the load; the capacity of the connection.

5.6.1. The initial data of the calculations

In all cases, the annual costs method [28] was used for the calculations below, although the NPV method is frequently used in economic calculations since in many cases, the payback period for PTL projects in rural areas is about twenty to thirty years; in other cases, such projects do not pay off altogether. The annual costs reflect the amount to be paid by the customer, operating the power facility in the design year, considering the construction costs, the loss costs, and the costs related to undelivered electricity.

At present and for the next three or four years, the bank interest rate for loans in the euro currency that are available for a large corporate customer with a good credit rating is within the range of 2 to 2.5 per cent. In our calculation, the bank interest rate is assumed to be 2.8 per cent, allowing a certain margin of error.

The total depreciation, maintenance and servicing costs for the 110-kV branch line, the 20-kV branch line, the new additional 20-kV line to be built as well as for the substation (a simplified substation as well as a H-type substation) have been assumed according to [28].

The cost of building one length unit of the combined 20-kV line has been assumed according to [53].

The electricity price has been assumed according to the average price of the year 2015 at the *Nord Pool Spot* exchange, i.e. 41.825 €/MWh, disregarding the trader's extra charge [54].

The values of some of the parameters, for example, the failure rate and the reinstatement time of the transformer, the failure rate and the reinstatement time of the power circuit-breaker, etc., have been assumed according to [55].

In compliance with the technical policies of the JSC "Sadales Tīkls" (the DSO) [56], the main 20-kV overhead power networks are built with a conductor cross-section of not less than 70 mm^2, using aluminium-steel or insulated wires. In the calculation, two conductor cross-sections were assumed: 70 mm^2, and 95 mm^2. In all the reviewed solutions, it was assumed that the 20-kV electric lines are designed as overhead lines, which is due to the fact that the construction of the SSs is mainly planned in rural areas, where the increase in electricity consumption will be 0 % according to the development plans of the JSC "Sadales Tīkls" (the DSO) (as compared to 1.5 % in cities). [59]

The permissible medium-voltage power network voltage drop for the calculations does not exceed ±5 % of the rated voltage of the power network.

Let us point out that the alternatives of setting up a connection with the capacities of 2.5 MW and 5.0 MW, which may be realistic at present and in the nearest future, are provided below at each of the discussed examples. In the examples below, it is assumed that one new additional 20-kV electric line will be built (an outgoing one), the length of which is a variable parameter, with assumed values of 5, 10, 15, 20, 30, 40, 50, 60, 70, and 80 km. The assumed maximum length of the 20-kV branch line is 20 km.

5.6.2. An example

The calculation conditions of the example

The assumed length of the 110-kV branch line is 0 km (the simplified substation is located under the existing 110-kV main electric line); the assumed length of the 20-kV branch line (the 20 kV line to be built from the simplified substation to the electric loads centre) is also 0 km (the connection load is located near the 110/20-kV simplified substation). The layout of the power supply connection alternative is shown in Fig. 5.5. The obtained results are shown in Figs 5.6–5.7.

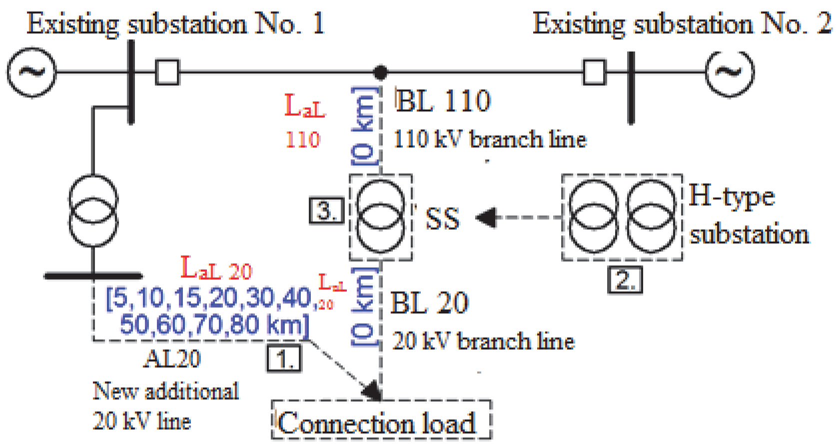

Fig. 5.5. Layout of a power supply connection alternative corresponding to the calculation conditions of Example 1.

The results of the example (the conductor cross-section of the new additional 20-kV line to be built is 70 mm²):

- at a connection capacity of 2.5 MW, it can be seen that the most cost-efficient alternative in setting up the network connection corresponds to the construction of a new additional 20-kV line if its length is up to 33 km (i.e. from the existing substations to the load). For the lengths exceeding 33 km, it becomes profitable to build a simplified substation; **however, considering the voltage losses**, the length of the additional 20-kV line to be built **is limited to 27 km;**
- at a connection capacity of 5.0 MW, construction of an additional 20-kV line becomes profitable already at a smaller length of the line (up to 20 km); **however, considering the voltage losses**, the length of the additional 20-kV line to be built **is limited to 13 km;**

- at a connection capacity of 7.5 MW, the length of the additional 20-kV line to be built is up to 13 km; **however, considering the voltage losses**, the length of the additional 20-kV line **is limited to 9 km;**
- at a connection capacity of 10.0 MW, the length of the additional 20-kV line to be built is up to 8 km; **however, considering the voltage losses**, the length of the additional 20-kV line **is limited to 7 km.**

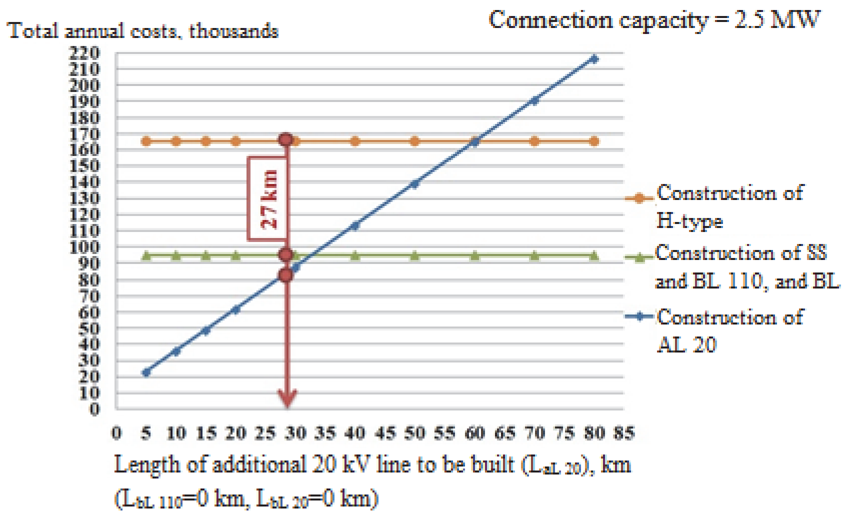

Fig. 5.6. Results of Example No. 1 with a connection capacity of **<u>2.5 MW</u>** and with an additional 20-kV line conductor cross-section of **<u>70 mm^2</u>**.

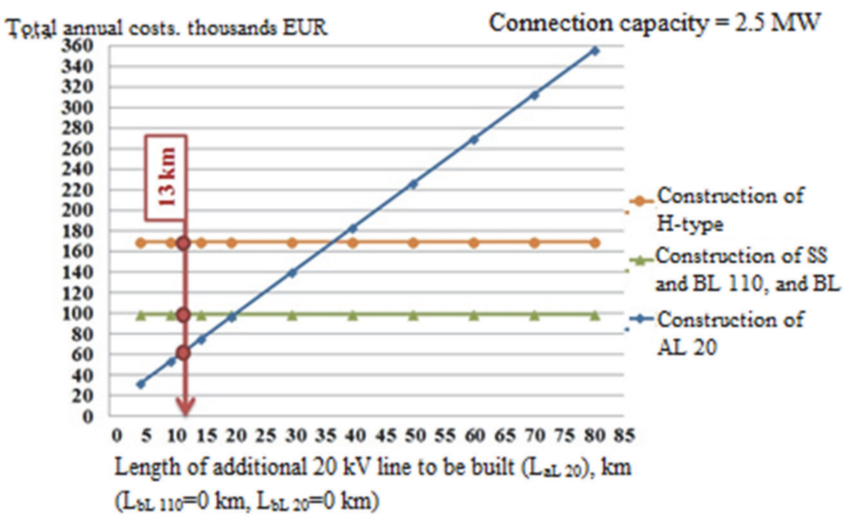

Fig. 5.7. Results of Example No. 1 with a connection capacity of **<u>5.0 MW</u>** and with an additional 20-kV line conductor cross-section of **<u>70 mm^2</u>**.

The results of the example (the conductor cross-section of the new additional 20-kV line to be built is <u>95 mm^2</u>):

- at a connection capacity of 2.5 MW, it can be seen that the most cost-efficient alternative in setting up the network connection corresponds to the construction of a new additional 20-kV line if its length is up to 32 km. For the lengths exceeding 32 km, it becomes profitable to build a simplified substation, **and, considering the voltage losses**, the length of the additional 20-kV line to be built **is also limited to 32 km;**

- at a connection capacity of 5.0 MW, construction of an additional 20-kV line becomes profitable already at a smaller length of the line (up to 23 km); **however, considering the voltage losses**, the length of the additional 20-kV line to be built **is limited to 16 km;**
- at a connection capacity of 7.5 MW, the length of the additional 20-kV line to be built is up to 15 km; **however, considering the voltage losses**, the length of the additional 20-kV line **is limited to 11 km;**
- at a connection capacity of 10.0 MW, the length of the additional 20-kV line to be built is 10 km; **however, considering the voltage losses**, the length of the additional 20-kV line **is limited to 8 km.**

6. CONCLUSIONS

Chapter 6 contains conclusions and recommendations for future work.

1. Restructuring of power systems and consideration of market mechanisms considerably change the formulation of the task of substantiating and optimizing energy facilities since the decisions have to be taken at the circumstances of wide price fluctuations.
2. The previously developed traditional methods of solving the planning optimization task have become outdated. Changes and checks are needed regarding the appropriateness of the traditional and existing approaches, and new appropriate methods need to be looked for.
3. Using the PLS-CADD software enables faster and more precise optimization of the design parameters of electric lines. As a result, it is possible to accurately assess the total capital investments for each overhead transmission line design alternative.
4. A stochastic approach is proposed, containing an algorithm considering the stochastic nature of the energy prices, the outdoor air temperature, and the loading of the lines.
5. The proposed algorithm makes it possible to determine the minimum total annual average costs and the corresponding optimal conductor cross-section, allowing to change the input data within a short time interval and to calculate the results.
6. Construction of simplified substations can provide considerable capital investment savings, which is widely used in many countries (Germany, the USA, Finland, Sweden, etc.).
7. Simplified substations represent one of the solutions that provide advantages to the user, i.e. the quality and reliability of power supply are improved alongside a decrease in the amount of investment needed for the new connection. Such a solution is substantiated by 110-kV substations that are technically designed according to present-day requirements and comply with the European standards (modern technologies for the protection of the network elements, reliable electric equipment of sound quality, probability of electric equipment failures diminished in comparison to the equipment manufactured in the 1960s–1990s, etc.).

8. The decision regarding the choice of the layout of a 110/20-kV substation simultaneously affects the interests of the transmission system operator and the distribution system operator, a clash of which may lead to technically and economically unsubstantiated solutions, for example, construction of a H-type substation.
9. The connection of a simplified substation to the high-voltage line (the TSO) with a branch line influences the operation of its relay-based protection and automation. The relay-based protection solutions proposed in the study enable minimization of the above-mentioned negative influence (using smart technologies — fast and reliable communication).
10. In all cases, the construction of a simplified substation needs to be substantiated with technical and economic calculations, considering the possibility of improving the reliability indicators and the possibilities of connecting new customers and improving the electricity sales. Groundless construction of substations may lead to unreasonable use of the capacity of the transformers and unnecessary 110-kV equipment operation costs.
11. The usefulness of building simplified substations depends on many factors (the size of the load, the layout of the loads, the distance from existing substations, the configuration of the medium-voltage network, the electricity price). Depending on the situation, either the construction of a simplified substation or the development of the medium-voltage network may become the most profitable solution.
12. In order to diminish the influence of 110-kV network faults on the power supply of the customers, it is proposed to use in the construction of simplified substations a standard layout with standard equipment, storing a reserve of the most important equipment of the layout (transformers, switches, disconnectors) to enable fast exchange of equipment in case of fault.
13. An analysis of the issues related to the operation of power networks in the neighbouring countries shows that the majority of simplified substations are at the disposal of the distribution network operators. Furthermore, standard simplified substations designed as frame buildings or container-type substations become unified facilities containing 110-kV equipment and, to a greater extent, 20-kV equipment. Considering the share of the 20-kV part in the operating expenses, it is advisable, as the economic efficiency of the simplified substation is assessed, to address the issue of the new SSs being taken over into the balance and maintenance of the DSO.
14. The consideration of the market conditions and the load changes when making decisions regarding the construction of simplified substations requires labour-intensive calculations, which can be automated by using specialized software, which can be synthesized with relatively small financial means.

BIBLIOGRAPHY

1. A. Martino, D. Fiorello, S. Shepherd, P. Pfaffenbichler. Strategic modelling of transport and energy scenarios, report: European Transport Conference 2006, Strasbourg/F, 18.09.2006–20.09.2006. In: Seminar: European Transport Policy and Research, 2006.
2. Junghāns, G., Oļeiņikova, I., Obuševs, A., Turcik, M.Kā veidojas elektroenerģijas tirgus cena? *Enerģija un Pasaule,* Nr. 1, 2012, 42.–45. lpp. ISSN 1407-5911.
3. https://en.wikipedia.org/wiki/Smart_meter
4. “Renewable Energy Sources”: Renewable and Appropriate Energy Laboratory, p. 12. Retrieved 06.12.2012
5. Šipkovs, P., Reķis, J., Palejs, D., Dubrovskis, V., Birzietis, G., Barons, P. u. c. Atjaunojamo energoresursu potenciāls Latvijā. Rīga: BEMA, 2008. 60 lpp.
6. Blumberga, A., Blumberga, D., Dzene, I., Gušča, J., Romagnoli, F., Vīgants, E., Veidenbergs, I. Atjaunojamās elektroenerģijas akumulācija. Rīga: RTU Izdevniecība, 2015. 238 lpp. ISBN 978-9934-10-748-1.
7. S. Massoud Amin and Bruce F. Wollenberg. Toward a Smart Grid. *IEEE power & energy magazine*, September/October 2005, p. 34–41.
8. Sauhats A., Žalostība D., Bočkarjova G., Bieļa-Dailidoviča E., Dinevičs J. Latvian Project of Smart Grid and Renewables Technological Park. From: Recent Researches in Environmental Science & Landscaping: Energy, Environmental and Structural Engineering Series 2. [Athens]: WSEAS Press, 2012, pp. 205–210.
9. Perfecting Business Processes in Electricity Grids by the Use of Innovative Technology of Demand Side Management in the Framework of the General Conception of Smart Grids. By: Klavsuts, Irina L.; Klavsuts, Dmitry A.; Rusin, George L. SEP 02.05.2014.
10. Chen-Ching L., McArthur S., Lee Seung-Jae. Smart Grid Handbook, 3-Volume Set, 2016, 1900 p. http://eu.wiley.com/WileyCDA/WileyTitle/productCd-1118755480.html
11. *Новости Электротехники*, Журнал №5 (71), 2011 год.
12. A. Ančuks. Viedo tīklu ietekme uz energosistēmas stabilitāti. RTU, Rīga, 2011. gads. Commission for Energy Regulation: Cost-Benefit Analysis (CBA) for a National Electricity Smart Metering Rollout in Ireland/ CER11080c. http://www.cer.ie/GetAttachment.aspx?id=64b7c398-b242-4966-947f-26490b18f117
13. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Smart Grids: from Innovation to Deployment/SEC (2011) 463 final.
14. Andrejs Koliškins, Inta Volodko. Varbūtību teorijas un statistikas elementi. Rīga, RTU izdevniecība, 2006. 81 lpp.
15. William W. Hines, Douglas C. Montomery, David M. Goldsman, Connie M. Borror. Probability and Statistics in Engineering, 2008. 672 pp.
16. L. Petrichenko, A. Sauhats, S. Guseva, S. Berjozkina, V. Neimane. The Stochastic Approach for Selecting Conductor of Power Line Based on the Monte Carlo method // EnergyCon 2014, Dubrovnik, Croatia, 13–16 May, 2014 (IEEE Xplore, ISBN 978-1-4798-2448-6).
17. И. М. Соболь. Метод Монте-Карло. М., 1985.
18. http://etap.com/
19. http://www.mathworks.se/help/econ/arima.forecast.html

20. PLS-CADD™ (Power Line Systems-Computer Aided Design and Drafting) User's manual, 2011, 468 pp.
21. AS "Sadales tīkls" 2012. gada slodžu pārskats.
22. AS „Sadales tīkls": AEUS (automatizētās elektroenerģijas uzskaites sistēmas) apraksts http://www.st.latvenergo.lv/pls/portal/docs/PAGE/LATVIAN/Sad_tikls/AEUS_apraksts.doc
23. Dace Plato. Viedie tīkli – jauna iespēja elektrību tērēt efektīvāk un lētāk. *Energo forums*, Nr. 6 (28), 2010. gada decembris.
24. Petričenko Ļ., Guseva S., Jankovskis N. Load Density Formation in Largest Cities. // Electronic Proceedings of the 55th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2014). Riga, Latvia: RTU, 2014. pp. 163–166.
25. Central Statistical Bureau of the Republic of Latvia. Population fertility and mortality.
26. В. М. Блок. Выбор оптимальных сечений кабеля с учётом экономических показателей. *Электрические станции*, № 9–10, 1945, стр. 8–12.
27. В. М. Блок. Электрические сети и системы. Москва, Высшая школа, 1986 г.
28. В. А. Веников, Ю. Н. Астахов. Экономические интервалы при выборе оптимальных вариантов энергетических объектов и их применение при технико-экономических расчётах электропередач. Известия академии наук СССР, Энергетика и автоматика, 1962, №3.
29. Э. Н. Зуев. Выбор основных параметров линий электропередачи районных электрических сетей в современных условиях. Методическое пособие. МЭУ. Москва: Информэлектро, 2003, 65 с.
30. Электрические системы. Электрические сети: учеб. для электроэнерг. спец. вузов // В. А. Веников, Л. А. Жуков, А. А. Глазунов и др.; Под ред. В. А. Веникова. 2-е изд., перераб. и доп. М. : Высш. шк., 1998, 510 с.
31. A. Vanags, Z. Krišāns. Elektriskie tīkli un sistēmas. Mācību grāmata, II daļa. Rīga: RTU Izdevniecība, 2005. 342 lpp.
32. F. Kiessling, P. Nefzger, J. F. Nolasco, U. Kaintzyk. Overhead Power Lines Planning, Design, Construction. Springer-Verlag Berlin Heidelberg New York: 2003, 759 p.
33. V. Neimane. On development planning of electricity distribution networks. Doctoral dissertation, Stockholm, 2001.
34. Berjozkina S., Petričenko Ļ., Sauhats A., Jankovskis N. Overhead Power Line Design in Market Conditions // Proceedings of the 5th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG 2015). Rīga, Latvija: IEEE, 2015. 5 pp.
35. G. Latorre, R. Cruz, J. Areiza. Classification of publications and models on transmission expansion planning. IEEE Trans. on Power Systems, Vol. 18, No. 2, May 2003, pp. 938–946.
36. R. Hemmati, R. A. Hooshmand, A. Khodabakhshian. Comprehensive review of generation and transmission expansion planning. *IET Generation, Transmission & Distribution*, Vol. 7, Iss. 9, April 2013, pp. 955–964.
37. M. O. Buygi, H. M. Shanechi, G. Balzer, M. Shahidehpour. Transmission planning approaches in restricted power systems. In: Proc. 2003 IEEE PowerTech, pp. 1–7.
38. Elektrostacijas pieslēgšanas kārtība: http://likumi.lv/doc.php?id=244670
39. S. Berjozkina, L. Petrichenko, A. Sauhats, S. Guseva, V. Neimane. The stochastic approach for conductor selection in transmission line development projects. In: Proc. 2014 IEEE International Energy Conf. (Energycon), pp. 557–564.

40. Petričenko Ļ., Sauhats A., Berjozkina S., Jankovskis N. Stochastic Planning of Distribution Lines. // Proceedings of the 13th International Conference on the European Energy Market (EEM 2016). Porto, Portugāle: IEEE, 2016. p. 5. (to be published)
41. Vides izglītības fonds (Ekoskolu programma): Klimata pārmaiņas, 36 lpp. http://www.videsfonds.lv/documents/publikacija-klimata-parmainas.pdf
42. K. Timmermanis, J. Rozenkrons. Elektrisko staciju un apakšstaciju elektriskā daļa. Rīga: Zvaigzne, 1988. 502 lpp.
43. Л. Н. Баптиданов, В. Л. Козис, Б. Н. Неклепаев, Б. В. Нечаев, М. Н. Околович, Л. А. Солдаткина, В. И. Тарасов, А. Л. Церазов. Электрические сети и станции (под редакцией Л. Н. Баптиданова). М.-Л.: Госэнергоиздат, 1963. С. 464.
44. Bevanger K., Bartzke G., Brøseth H., Dahl E. L., Gjershaug J. O., Hanssen F., Jacobsen K. O., Kvaløy P., May R., Meås R., Nygård T., Refsnæs S., Stokke S., Thomassen J. Optimal design and routing of power lines: ecological, technical and economic perspectives (OPTIPOL). Progress Report – NINA Report 762, 2011, p. 52.
45. A. Ļvovs. Elektroapgādes drošuma līmeņa tehniski-ekonomiskās regulēšanas metodoloģijas izstrāde. Promocijas darbs. Rīga: RTU, 2013. 156 lpp.
46. Dr. N. Loganathan, A. Pavithra. Distinguishing the Various Faults in Transformer and its Protection Using Support Vector Machine. *International Journal of Advanced Research in Electric, Electronics and Instrumentation Engineering*, Vol. 4, Iss. 2, 2015, pp. 568–573.
47. ENTSO-E: Nordic grid disturbance statistics 2013, 2014, 64 pp.
48. G. Gavrilovs. Apvienotas ekspluatācijas pieejas izstrāde lieljaudas transformatoru tehniskā stāvokļa noteikšanai. Promocijas darbs. Rīga: RTU, 2012. 118 lpp.
49. ABB Power Technologies, PASS M0 Innovative solutions for distribution substations up to 170 kV, March 2005, p. 20.
50. Siemens, „Containerized” high-voltage substation: http://www.energy.siemens.com/hq/en/power-transmission/high-voltage-substations/
51. Hermann J. Koch. Gas insulated substations. First Edition. IEEE Press-John Wiley & Sons Ltd, 2014. 490 pp.
52. Vadošie energosistēmu projektēšanas norādījumi un normatīvi: Nr. 9484TM-T6 // Энергосетьпроект. М.: 1981.
53. AS „Sadales tīkls” 2014. gada sadales sistēmas būvdarbu vidējās faktiskās izmaksas pieslēguma maksas aprēķinam: http://www.sadalestikls.lv/files/newnode/pieslegumi/pieslegumieur/2015-03-24_sludin_vid_izm_2014g.pdf
54. Nord Pool Spot datubāze: http://www.nordpoolspot.com/
55. Fredrik Roos, Sture Lindahl. Distribution System Component Failure Rates and Repair Times – An Overview, 2004, 6 pp.
56. Technical policy of JSC “Sadales Tīkls” (confirmed on July 9, 2014).
57. Annual financial statement of JSC “Sadales Tīkls” (2014): http://sadalestikls.lv/files/newnode/parskati/2014.gada%20parskats.pdf