RIGA TECHNICAL UNIVERSITY

Faculty of Power and Electrical Engineering

Institute of Power Engineering

Lubov PETRICHENKO

Doctoral student of the Power Engineering Doctoral study programme

FEASIBILITY STUDY OF THE SELECTION OF URBAN NETWORKS PARAMETERS UNDER MARKET PRICE CONDITIONS

Summary of the Doctoral Thesis

Scientific supervisor:
Dr. Sc. Ing., Assoc. Professor
S. GUSEVA

Dr. Habil. Sc. Ing., Professor
A. SAUHATS

Riga, 2014

Petrichenko L. Feasibility study of the selection of urban networks parameters under market price conditions. Summary of the doctoral Thesis – R.: RTU, 2014.– 43 pp.

Printed in accordance with decision No. 16/14 of RTU Doctoral Board P-05 (Power and Electrical Engineering) dated November 13, 2014.

This Thesis has been supported by the European Social Fund within the project "Support of the implementation of doctoral studies at Riga Technical University".

This work has been supported by the program «LATENERGI», Project Nr. 2" Optimization of power system development planning, energy production, selling and distribution"

ISBN 978-9934-10-628-6

DOCTORAL THESIS
SUBMITTED TO RIGA TECHNICAL UNIVERSITY
TO OBTAIN DOCTORAL DEGREE IN ENGINEERING

Doctoral Thesis is proposed for achieving Dr. sc. ing. degree and will be publicly presented on the 27th of November 2014 at Faculty of Electrical Engineering of Riga Technical University, Azenes str. 12/1, in room 306, at 16.00.

OFFICIAL OPPONENTS

Professor, *Dr. sc. ing.* **Inga Zicmane,**
Riga Technical University

Dr. sc. ing. **Aleksandr Gavrilov**,
JSC "Sadales Tīkls", Electrical Engineer

Dr. sc. ing. **Robert Neiman**,
Application Specialist, Megger Sweden AB, Stockholm, Sweden

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 Doctoral Thesis is not submitted to any other university for achieving scientific degree.

Lubov Petrichenko .... (signature)

Date ....

Doctoral Thesis is written in Latvian language and consists of an introduction, 5 chapters, conclusions and list of references. The total volume of the Thesis is 178 pages (including an appendix which consists of 47 pages). The Thesis contains 16 tables and 78 figures. The list of references consists of 118 literature sources.

CONTENTS

GENERAL DESCRIPTION OF THE WORK

The Topicality of the Doctoral Thesis

The power supply systems of large cities are component parts of the power system of a country or its region. The creation of power supply systems of large cities (LCPSS) and the necessity for analyzing the parameter optimization is determined by the intensive dynamics of the number of cities, their territories, the number of population in different countries, the composition of electricity consumers and the installed power, along with continued electrification of everyday life, improvement of the services sector and ensuring of the life processes of population.

The electric power networks of cities are characterized by a multifaceted composition of consumers: dwelling houses, industrial, public utility and services enterprises, electrified city and intercity transportation and others. Various groups of consumers significantly differ in terms of consumer capacity, operating modes, requirements regarding the quality of electric power and the uninterrupted operation of power supply. In the layout of substations and construction of power transmission lines, it is necessary to consider architectural, urban construction and environmental limitations as well as the established tradition of urban planning. The performance of the task of designing electric power systems of cities is compounded by large amounts of normative acts or by lack of initial information. The power supply system has to meet a number of contradictory requirements: reliability, electric safety in operation, and required quality of electric power [1–3].

In the creation and development of electric power networks, it is necessary to consider the possibilities of gradual development, both in terms of the capacities of the transformers of the substations as well as the transfer capability of the power transmission line and the voltages of the supplying networks. The above-mentioned factors determine continuous development of electric power networks in space and time as well as increase of the load of the power supply systems of large cities.

Creation of new electric power networks as well as extension or reconstruction of the existing ones requires considerable material, financial and labour resources. These are required for electrical equipment and for performing works of construction, installation, bringing into order and others. It has to be taken into account that the funds invested into construction as well as reconstruction of power facilities do not ensure economic profit until the moment operation is started. Therefore, it is necessary to perform evaluator technical and economic calculations, determining the proportions of funds for the construction of new power facilities and the reconstruction of the existing ones.

Optimum development of a complicated, dynamic LCPSS requires in-depth scientific research applying system analysis methods, considering the dynamics of the changes of the equipment parameters and an increase in the consumer loads for the whole city power supply system. The difficulty of solving the tasks of optimum development and rational construction of networks can be explained by the fact that these tasks are solved at the conditions of incomplete and uncertain information about the timeframes of putting into operation individual facilities as well as lack of reliable data regarding the loads of prospective consumers and detailed designs of buildings and structures in certain districts of a city [4–6].

At these conditions, it turns out that it is difficult to find a solution to the complex task of optimum LCPSS development as a global system. In the search for a decision, a complex task is divided into a number of local optimization tasks, considering the requirements that appear on the part of the global system as well as other external sides regarding the local system. Given this condition, the optimum plan of an individual subsystem, with a certain relative error, is contained as a component part within the optimum development plan of the global system.

For solving these tasks, a great number of studies have been developed and many tools have been worked out. Considerable contribution in this area has been made by both foreign and Latvian researchers: Z. Krišāns, A.Vanags, E.Vanzovičs, K.Lariņš, R.Zebergs, A.Sauhats, S.Guseva, I.Oleinikova, V.Blok, V.Kozlov, V.Idelchik, J.Konyukhova, I.Tulchin, J.Astakhov, V.Venikov, P.Grudinsky, J. Priklonsky, G.Pospelov, E.Zuyev, D.Faybisovich, V.Neimane and others. Probably because of the complicated nature of power industry problems and the limited character of technical resources, the majority of the research conducted in the 20th century limits itself to largely simplified statements of optimization tasks. Also, methodological directions, technical standards and traditional solving methods have become outdated. As a result, changes and verifications are needed regarding the suitability of the traditional and existing approaches.

The present Doctoral Thesis is dedicated to solving individual tasks of rational formation of power supply systems of large cities in the example of Riga city (the capital of Latvia). The presented and technically and economically substantiated choice of parameters is an important stage in rational designing of the electric power networks of cities. This issue is topical in the power industry at any stage of the development process. The obtained solutions can be used in the power supply systems of Riga, other cities of Latvia and other cities abroad for working out the optimum development strategy.

All the above aspects and the topicality of discussing them have determined the choice of the subject, goals and content of the present Doctoral Thesis.

The goal and the tasks solved by the Thesis

The goal of the Thesis is to develop a methodology for rational designing of distribution networks, which is based on general transmission network simulation and formation principles and criteria; to propose the technical and economic substantiation of the choice of the optimum parameters of the city network at the conditions of incomplete and uncertain information. To achieve the set goal, the Thesis solves the following tasks:

1. Analysis of determined and stochastic determination and forecasting methods of power supply system load elements.
2. Analysis of energy prices' prediction.
3. Determination of the perspective load of a medium-voltage transformer substation on the basis of the city districts' load densities.
4. Research of load densities of city districts, its' cartogram development and data collection of districts' preliminary load densities.
5. Creation of a methodology for choosing the cross-section of electric power networks under the market prices conditions.
6. Analysis of stochastic approach for choice of high voltage line parameters and appropriate software development.

The scientific novelty of the Thesis

1. Development of methodology for rational designing of city distribution networks, based on general transmission network simulation and formation principles and criteria;
2. Forecast of electricity price using neural network method.
3. Modification of the economic intervals method for the choice of the optimum cross-section of cable lines and overhead lines with a nominal voltage of 330-0.4 kV under market economy conditions;

4. Implementation of a stochastic approach to the choice of the parameters of city networks by means of the Monte-Carlo method, considering the fluctuations of actual electricity prices, loads and ambient temperature;
5. Proposing a method for planned adjustment of the load densities of various districts of Riga city and substation service areas at various voltage levels;
6. Development of software ensuring the improvement of distribution networks design.

The research methods and tools

1. Geometric and mathematical simulation of the objects under consideration.
2. Traditional and modern load and energy price forecasting methods.
3. Non-linear and Monte-Carlo optimization methods for solving development tasks.
4. The economic intervals method for choosing the optimum cross-section.
5. The ArcGIS and AutoCAD graphical software.
6. Microsoft Office Excel software, the MathCAD system, the Matlab interactive environment for solving engineering problems, intensive computing, visualization and analysis of results.

The practical applicability of the Doctoral Thesis

The methodologies and algorithms proposed in the Thesis can be used in the following ways:

- in theoretical and scientific related to rational construction of city power supply systems and optimization of their parameters;
- in power industry enterprises, organizations, and companies that deal with issues related to the development and designing of city power supply diagrams;
- for designing new 20-10/0.4 kV transformer substations and 0.4 kV networks, using the main patterns that have been found out.

The results of the work are applied in:

- Universal nomograms are used in educational process for engineers and master degree students preparation in power engineering department.
- State Program Power engineering Project Nr.7 „Decreasing of Climate Changing and Integration of Renewable Energy Resources Technologies into Latvian Power System” (Scientific advisor professor Antans Sauhats);
- Agreement (RTU with Latvenergo, signed in 2013, planned to be completed in 2015) for the investigation of JSC „Latvenergo” electric stations regimes planning program development”.

Some particular issues were considered in the Master’s Thesis of the author, which then were additionally included into the following projects:

- Riga Technical University and JSC „Latvenergo” contract No. 7310 (Nr.010000/08-16) „Development of Riga City perspective power supply network until the year 2020” scientific advisor Janis Rozenkron, (participation in developing separate issues);;
- Contract with Marupe district council, No. 5-21/-2012 from 23.04.2012. „The feasibility study of new 110 kV transformer substation in Marupe region”; scientific advisor Janis Rozenkron, (participation in developing separate issues).

The personal contribution of author to performed research

The foundation of the main theses to be defended is made up by ideas that were devised in close co-operation with Associated Professor Svetlana Guseva and Professor Antans Sauhats. The present Doctoral Thesis can be considered as a continuation of the long-term work of professors.

Selection of urban load parameters of electrical networks, using common formation principle, is carried out together with *dr.sc.ing.* Natalja Skobeleva.

The verification of the ideas, the technical and economic models of the city power supply system, the required software, the numerical experiments and their analysis as well as the recommendations for efficient application belong personally to the author.

Approbation of the Doctoral Thesis

The research results have been discussed at 7 international conferences:

1. The 51st RTU Annual International Scientific Conference 2010. "Load Determination and Selection of Transformer Substations' Optimal Power for Tasks of Urban Networks' Development", Faculty of Power and Electrical Engineering, Riga, 1 Kronvalda Blvd., October 14, 2010.
2. The 6th International Conference on Electrical and Control Technologies. "An Integrated Approach to the Formation of Service Areas for Urban Substations of Different Voltage", Kaunas, Lithuania, May 5–6, 2011.
3. The 10th IASTED European Conference "Power and Energy Systems". "Urban Power Supply System's Development in Conditions of Uncertain Information", Crete, Greece, June 22–24, 2011.
4. The 52nd International Scientific Conference of Riga Technical University on Power and Electrical Engineering. "The Choice of Optimum Cross Section for Overhead Line by Economic Intervals Method", October 14–15, 2011.
5. The 7th International Conference on Electrical and Control Technologies (ECT 2012). "Economic Intervals' Method for Choice of Line Cross-Section and Its Realization in Matlab Software", Kaunas, Lithuania, May 3–4, 2012.
6. The 11th International Conference "Energy-Ecology-Economy 2012". "Approach of Optimum Cross-Section Choice for Cable Lines in Market Prices Conditions", High Tatras – Tatranske Matliare, Slovakia, May 15–17, 2012.
7. The 55th International Scientific Conference on Power and Electrical Engineering of Riga Technical University. **"**Probabilistic Method for Selection of Power Line Wire Type and Cross-Section", "Load Density Formation in Largest Cities", Riga, Latvia, October 14, 2014**.**

The results obtained in the frames of development of the Thesis are included in 17 publications in international proceedings:

1. Svetlana Guseva, **Lubov Kozireva**, Nataly Skobeleva. Large Urban Load Determination in Conditions of Uncertain Information // Power and Electrical Engineering, Ser. 4, Vol. 26, Riga, RTU, Latvia, 2010, p. 27–33 (*EBSCO, ProQuest, Versita, VINITI,* ISSN 1407-7345).
2. S.Guseva, O.Borscevskis, N.Skobeleva, **L.Kozireva**. Load Determination and Selection of Transformer Substations' Optimal Power for Tasks of Urban Networks' Development //Power and Electrical Engineering, Ser. 4., Vol. 27, RTU, Latvia, 2010, p. 31–36 *(quoted: EBSCO, ISSN 1407-7345)*.

3. S.Guseva, O.Borscevskis, N.Skobeleva, **L.Petrichenko**. Perspective Loads of Transformer Substations at Development of Urban Power Supply Systems // Proceedings of the XV International Scientific Conference “Present-day problems of power engineering APE’11”, Vol. III, 8–10 June, Gdansk-Jurata, Poland, 2011, p. 51–59 (Journal “Acta Energetica” ISSN 2080-7570, 2012 | nr 2 | 71–82).
4. S.Guseva, O.Borscevskis, N.Skobeleva, **L.Petrichenko**. Urban Power Supply System’s Development in Conditions of Uncertain Information // Proceedings of the tenth IASTED European Conference “Power and Energy Systems”, Crete, Greece, 2011, p. 27–31 (SCOPUS).
5. S.Guseva, **L.Petrichenko**. The Choice of Optimum Cross Section for Overhead Line by Economic Intervals Method // Power and Electrical Engineering, Ser. 4, Vol. 29, Riga, RTU, Latvia, 2011, p. 37–42 (ISSN 1822-5934).
6. S.Guseva, **L.Petrichenko**. Approach of Optimum Cross-Section Choice for Cable Lines in Market Prices Conditions. Power Engineering 2012, High Tatras – Tatranske Matliare, May 15–17, 2012, Slovakia, p. 87–88.
7. S.Guseva, **L.Petrichenko**. Economic Intervals' Method for Choice of Line Cross-Section and Its Realization in Matlab Software // Proceedings of the 7th International Conference on Electrical and Control Technologies, ECT-2012, May 3–4, 2012, Kaunas, Lithuania, p. 221–226 (*indexed ISSN 1822-5934*).
8. N.Skobeleva, O.Borscevskis, S.Guseva, **L.Petrichenko**. An Integrated Approach to the Formation of Service Areas for Urban Substations of Different Voltage. Journal of Energy and Power Engineering (ISSN1934-8975), David Publishing Company, Inc. USA, Vol. 6, No.8., August, 2012, p.1358–1362 (Database of EBSCO, Massachusetts, USA; Database of Cambridge Science Abstracts (CSA), USA Ulrich's International Periodicals Directory,USA; Chinese Database of CEPS, American Federal Computer Library center (OCLC), USA; Summon Serials Solutions).
9. Guseva S., **Petrichenko L**. Choice of the Optimum Cross-Sections for 20-110-330 kV Overhead Lines under Market Conditions // Latvian Journal of Physics and Technical Sciences, No. 6(1) (Vol. 49), Riga, Latvia, 2012, p.13–22.(ISSN 0868-8257, SCOPUS)
10. Guseva S., **Petrichenko L.** The Modified Method of Economic Intervals for High-voltage Overhead Lines // Materials of the XVIII All-Russia Scientific and Technical Conference “Power: Efficiency, Reliability, Safety”, December 3–7, 2012, Tomsk, Russia, p. 111–113.
11. S.Guseva, **L. Petrichenko**, N.Skobeleva. Load Density Distribution and Assessment for Urban Power Supply System // The 4th International Conference on Power Engineering, Energy and Electrical Drivers, May 13–17 2013, Istanbul, Turkey (SCOPUS).
12. S.Guseva, **L.Petrichenko**. Choice of 0.4 kV Cable Cross-Sections by Economic and Technical Criteria under Market Conditions // Power and Electrical Engineering, Vol. 31, Riga, Latvia, 2013, p. 38–42 (EBSCO, ISSN 1407-7345).
13. **L.Petrichenko**, A.Sauhats, S.Guseva, S.Berjozkina, V.Neimane. The Stochastic Approach for Determination of Transmission Line Wire Cross Section // The 2014 International Conference on Power Systems, Energy, Environment. Interlaken, Switzerland, February 22–24, 2014, (ISI (Thompson Reuters), ELSEVIER, SCOPUS, Zentralblatt MATH, British Library, EBSCO, SWETS, EMBASE, CAS-American Chemical Society, EI Compendex, Engineering Village, DoPP, GEOBASE, Biobase, TIB/UB-German National Library of Science and Technology, American Mathematical Society (ANS), Scholar Google (IEEE)).

14. **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, May 13–16, 2014 (IEEE Xplore, ISBN 978-1-4798-2448-6).
15. **L.Petrichenko**, A.Sauhats, S.Berjozkina, V.Neimane. Probabilistic Method for Selection of Power Line Wire Type and Cross-Section // Proceedings of the Riga Technical University 55th International Scientific Conference on Power and Electrical Engineering, Riga, October 14–17, 2014, p.141–144 (SCOPUS).
16. **L.Petrichenko**, S.Guseva, N.Jankovskis. Load Density Formation in Largest Cities // Proceedings of the Riga Technical University 55th International Scientific Conference on Power and Electrical Engineering, Riga, October 14–17, 2014, p.163–166 (SCOPUS).

The structure and content of the Doctoral Thesis

Doctoral Thesis is written in Latvian language and consists of an introduction, 5 chapters, conclusions, and a list of references, 46 appendixes, 78 figures and illustrations, 16 tables, 178 pages in all. The list of references consists of 118 literature sources.

Chapter One is dedicated to a description of 330, 110, 20-10 and 0.4 kV networks condition of the power supply system, technical data and development perspectives of Riga city. Assignment approach and mathematical formulation of city power supply is described.

Chapter Two summarizes and analyzes information of calculation loads methods of large cities and their districts. The load forecast of Latvia and Riga has been done till the year 2030 according to various scenarios. The neural network method has been detailed analyzed and used for city load and energy prices prediction.

Chapter Three analyzes and evaluates the issue regarding the determination of the prospective loads of transformer substations of various voltage levels, based on load densities and the service areas of substations in the territory of Riga. Cartograms regarding the load densities of city districts (microdistricts) have been developed. The work has been implemented by using the ArcGIS, EXCEL and AutoCAD software.

Chapter Four proposes a modified economic intervals method for choosing the optimum cross-section under market economy conditions. The graphical user interface in the Matlab programming environment is created, which helps to calculate both 0.4-10-20-110-330 kV overhead lines and 0.4-10-20-110-330 kV cable lines.

Chapter Five proposes and implements a stochastic approach to the choice of high-voltage parameters. As an example, the study shows rational choice of 110 kV and 330 kV overhead lines based on the stochastic approach based method (Monte-Carlo method).

1. DESCRIPTION OF LATVIA AND RIGA CITY POWER SUPPLY SYSTEM

1.1. Description of Latvian power system

The power networks of the Latvian power system ensure power supply in the territory of the whole country.

The electric power consumption in Latvia in the period from 2000 till 2013 is presented on Fig. 1.1 [7, 8].

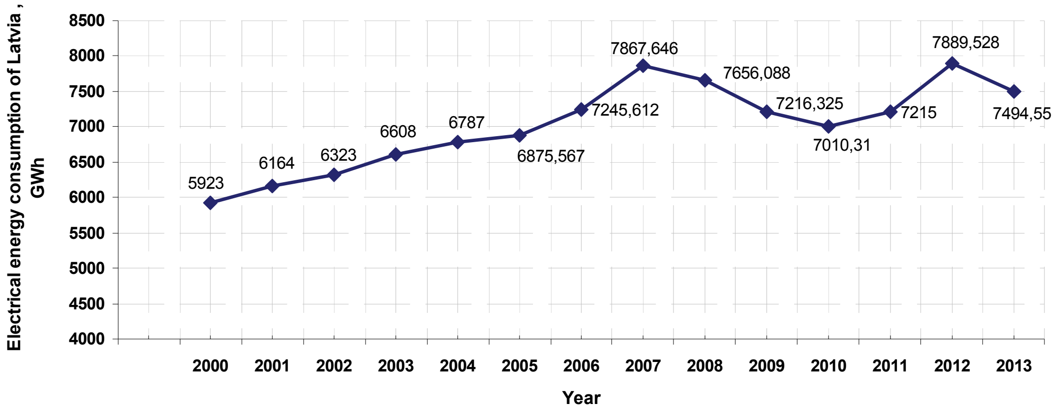


Fig. 1.1. Electrical energy consumption of Latvia in 2000–2013

In accordance with the data collected by the distribution system operator, the total electric power consumption by end consumers in Latvia in 2012 was 7859 GWh (with power losses), which is by 8.2 % more than in 2011 (7215 GWh). This is the largest increase since the regaining of national independence. Up to this moment, the largest consumption increase was observed in 2007 when the consumption increased by 7.9 % [9].

The transmission and distribution of electric power in the territory of Latvia is ensured by 330-110-20-10(6)-0.4 kV power networks. At the end of 2013, the overall length of 110-330 kV power transmission lines was 5275 km (measured by the circuit); thereof 76 %, or 4009 km, is made up by 110 kV lines and 24 %, or 1266 km, by 330 kV lines. The total length of medium voltage and low-voltage electric power lines at the end of 2013 was 94 705 km [8].

To ensure the operation of the transmission network, fifteen 330 kV substations with a total autotransformer capacity of 3575 MVA and one hundred and twenty-two 110 kV substations with a total transformer installed capacity of 4968 MVA are used.

The number of distribution network transformer substations is 29 275 whereas the number of transformer substations is 26 391 and their total installed capacity is 5 809 MVA.

1.2. Description of Riga power supply system (RPSS)

The consumption of the capital of Latvia is about 30 per cent of the summary capacity of the power system. The electric energy consumption of Riga city in the period from 2000 till 2013 is shown on Fig. 1.2 [10].

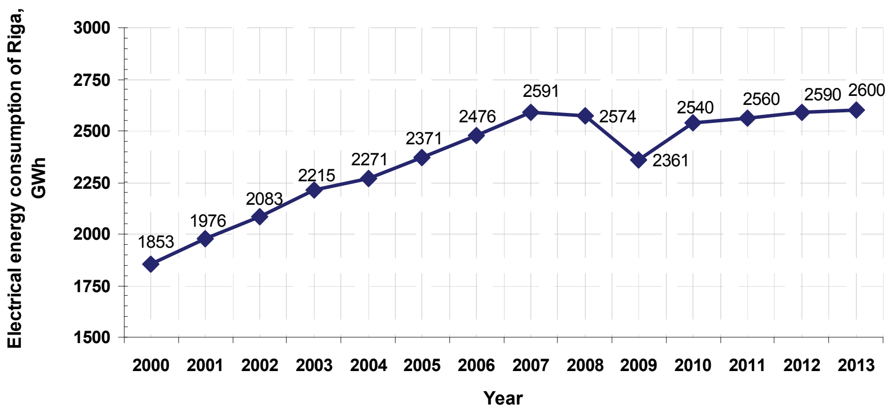


Fig. 1.2. Electrical energy consumption of Riga in 2000–2013 [10]

At the end of 2013, the overall length of the 110...330 kV power transmission lines in Riga city was 320 km (measured by the circuit), whereof 78 %, or 250 km, is made up by 110 kV lines and 22 %, or 70 km, is made up by 330 kV lines. The overall length of medium voltage lines was 2300 km (99.4 % thereof – cable lines) and the length of low-voltage power lines was 2600 km (90.7 % thereof – cable lines) [11].

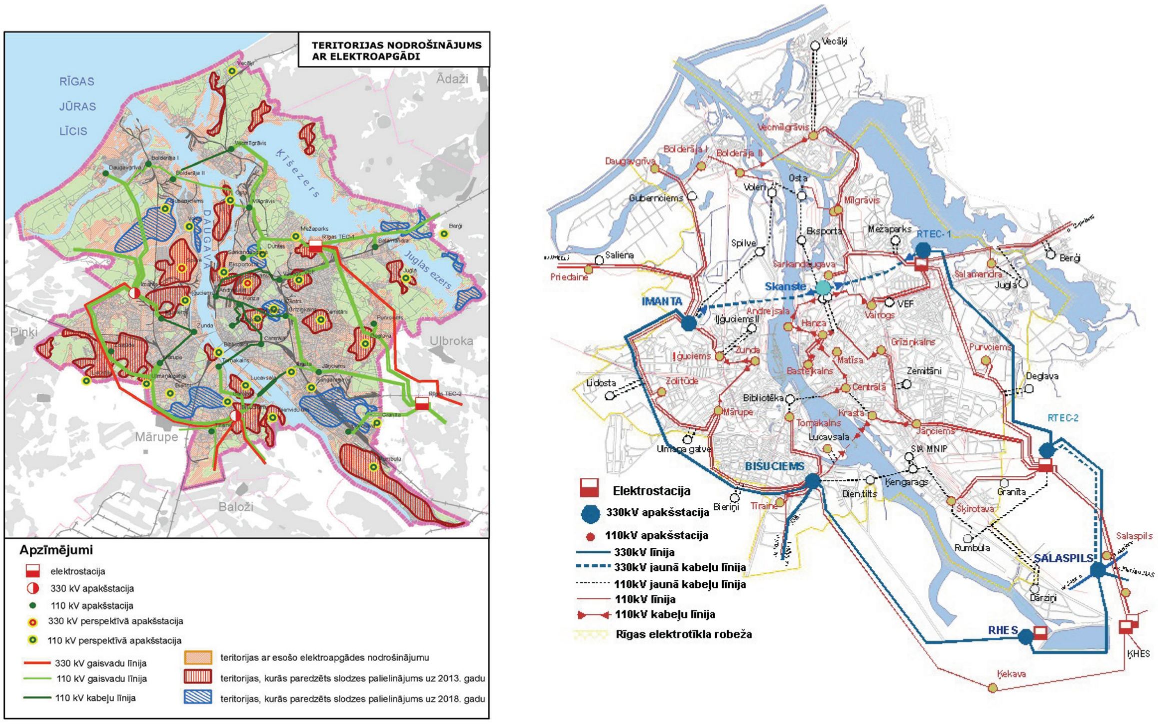
The consumers of Riga mainly receive electricity from the 330...110 kV power networks of the power system, from three 330/110 kV transformer substations situated in Riga (Imanta, Riga TEC No. 1, Bišuciems) and twenty-eight 110 kV substations.

According to the data of JSC „Latvenergo" for 2013, the total number of 6-20/0.4 kV transformer substations in Riga was 2130, with a total capacity of 1300 MVA. The number of 10 kV distribution points is 78.

1.3. The development perspectives of RPSS

The continuous load increase in Riga city in a historical development view causes thoughts about the suitability of the power grid of the city for the current load demand as well as about the readiness for supply of the prospective loads [10]. In accordance with the Riga Development Masterplan for the years 2006–2018, new territories for ensuring power supply have been planned [11]. Fig. 1.3.a provides a map of the prospective power supply in Riga city [12].

For further development of city power supply, the Board of Experts of JSC "Latvenergo" adopted the "Riga High-Voltage Network Diagram by 2020" at its meeting of January 15, 2010 (see Fig. 1.3.b). The working out and adoption of the diagram is a very important stage in the directed development of the power supply of the city.



a.) b.)

Fig. 1.3. a.) A map of the future power supply of Riga City.
b.) A diagram of the Riga high-voltage network up to 2020
(to be discussed by the Expert Council of JSC "Latvenergo")

One of the goals of this diagram is to determine new load centres, new 110 kV substations and their possible locations, based on the City Development Masterplan for the years 2006 –2018 worked out by Riga City Council, Riga long-term Development strategy by the year 2025 and taking into account the planned character of construction in the territory of the city [11].

The diagram provides for building more than twenty new 110 kV substations. Due to the consequences of the economic crisis, there may be changes to this development plan. The deadlines for introducing new substations are postponed, the sequence of introducing the substations changes and the construction of some of the substations will not be topical until the end of the prospective plan. The implementation of the plan will be continued in the future and the network development concept will be retained.

Therefore, the city power supply diagram is to be perceived as a prospective one, which is to be defined more precisely over time as additional information is acquired.

1.4. The statement and mathematical formulation of the task of urban power supply

1.4.1. Power supply requirements

When designing urban power supply, the internationally recognized requirements shall be taken into account, which are formulated for power industry on the whole [13]. The power supply shall be cost-effective, safe, environmentally friendly and sustainable.

This problem, being understandable in substance, is associated with the necessity of solving various extremely complicated tasks:

1. It is necessary to forecast the demand and prices of energy for many years forward.
2. The optimum configuration is to be chosen from the extremely great amount of the possible configurations (diagrams) of the electrical network.
3. The parameters of a great number of equipment are to be selected (transformer capacities, cross-sections of line conductors, location of substations, etc.).
4. The urban development process is to be taken into account. The power supply system should be adapted to time-varying urban requirements.
5. The possible appearance of opponent and, perhaps, partner power supply business shall be foreseen (the distributed energy sources, the renewable energy sources).

It is necessary to point out that the conditions of urban power supply planning problem have rapidly changed over the last years in passing to the use of market mechanism. The changes, primarily, cause major fluctuations in energy prices. A question about the possibilities of using the urban power supply methodology that was being developed for many years appears. It is so, because all the "classical" methods are based on prices that are average and time-unvarying.

When passing to the mathematical formulation of the problem, the above-mentioned requirements and tasks result in the necessity of formulating tasks in the multi-criteria, non-linear, stochastic and dynamic form [14].

The tasks of the mentioned form are solved by assuming a number of simplifications and, in many cases, by using designer's experience and knowledge. [13–16]. Also, the present paper is not exception. The following basic assumptions are used:

1. The economical efficiency is assumed as the basic requirement. It is considered that the rest of requirements are taken into account by fulfilling the corresponding rules and standards that regulate the requirements regarding reliability, environment and sustainability.
2. The optimization task is solved, using the static approach.
3. The influence of the competitors is not taken into account (the game theory methods are not used [13]).

1.4.2. Statement, decomposition and scheme of the optimization task

The total consumed electric power of modern cities can reach a value of tens gigawatts. In order to ensure such an output, a number of powerful electric power plants and super-high voltage network are required.

Most urban consumers require electricity through a low-voltage network. To ensure the connection of two voltage levels mentioned above, two more voltage levels are usually used (110 kV and 6-10(20) kV).

As a result, it can be stated that the electrical network of a city contains hundreds of thousands elements, which leads to the necessity of searching for simplifications in the statement of the optimization task.

A method based on using the geometrical simulation principle is the most usable and developed method [16–19].

According to the practice of this method, a city is covered by hexagon-shaped transformer service areas [16, 18], the radius of which depends on the load density and the nominal capacity of a transformer substation.

As a result of the geometrical simulation, the city is divided into hexagons, which, in terms of the optimization task, makes it possible to decompose it into several, considerably more simple parts. This decomposition is strongly dependent on the load density (the value of power per square kilometer). The following two chapters of the doctoral paper are dedicated to that particular determination and correction of the load density.

2. LOAD AND ENERGY PRICE CALCULATION AND FORECASTING METHODS OF CITIES AND CITY DISTRICTS

The Chapter two summarizes and analyzes information of calculation loads methods of large cities and their districts. For analyzing and summarizing the estimated loads, data has been used from Latvian and foreign bibliography sources and instructive materials [20–22]. A big attention is focused to load and energy price forecasting. Neural network and scenario methods are used for its' prediction. [23].

The classification of load and energy prices calculation and forecasting methods is given in Fig. 2.1.

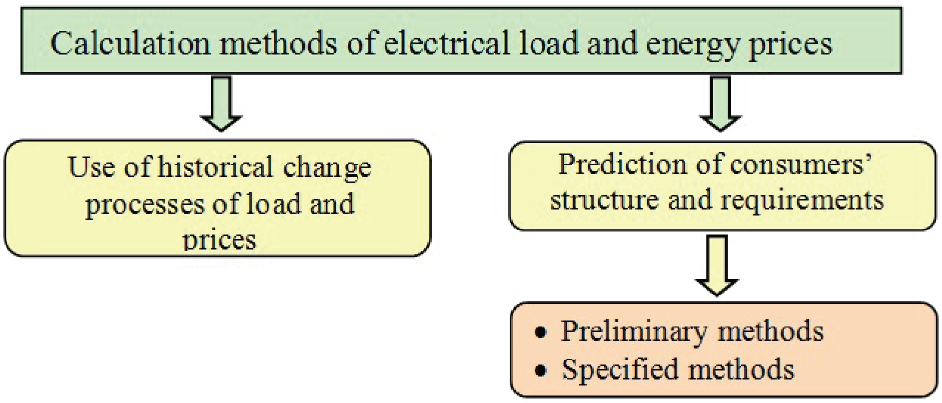


Fig. 2.1. Urban total electrical load and energy prices calculation methods

2.1. Urban and suburban load determination methods

In conditions of incomplete and uncertain initial information for load determination of big city's new microdistricts, can be used only preliminary methods. In [16, 20–22] is summarized the information of following methods and practical calculations are done.

The most complete calculation of the estimated load is performed by consecutive summarization of the electric loads of the elements of the power supply system (Fig. 2.2).

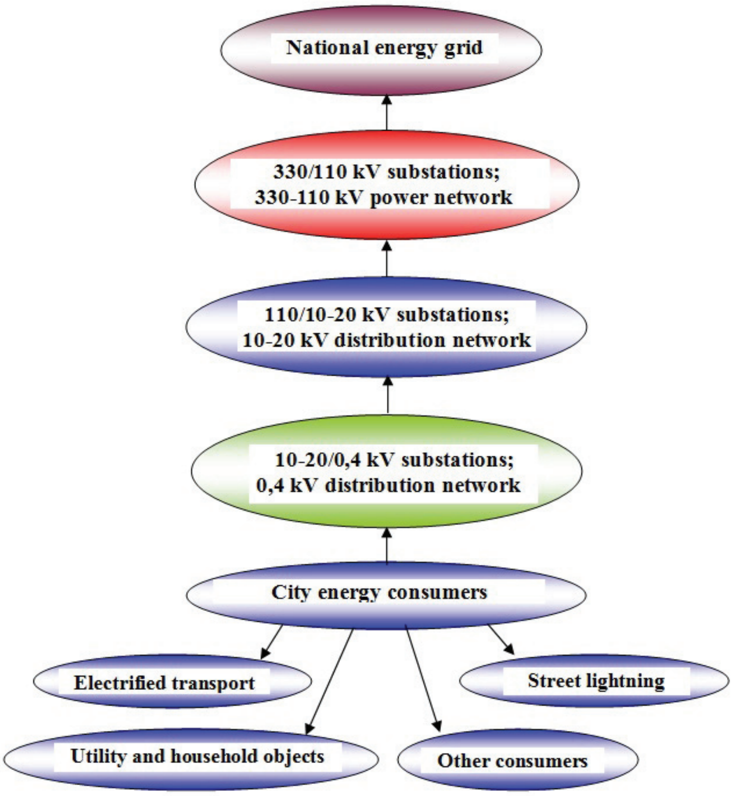


Fig. 2.2. Urban load determination algorithm after sequential generalization of the loads of network elements

2.1.1. Total electrical load determination of different voltage levels

A number of recommended calculation alternatives for calculating the estimated loads of dwelling houses are proposed [20–22].

The load of 0.4 kV distribution network

Alternative 1

In the general case, the estimated active load $P_{dwel.h}$ of a dwelling house is calculated according to the expression (2.1) [21, 22]:

$$P_{rat.dwel.h.} = P_{dem.fl.} n_{fl.} k_{dem.}, \quad (2.1)$$

where $P_{dem.fl.}$ is the demanded capacity per flat, kW/flat; $n_{fl.}$ is the number of flats; $k_{dem.}$ is the demand coefficient depending on the demanded capacity of the flats.

Alternative 2

The estimated load depends on the specific flat load and is calculated by the following expression [20–22]:

$$P_{rat.dwel.h.} = P_{specif.fl.} n_{fl.} , \tag{2.2}$$

where $P_{specif.fl.}$ is the estimated specific load per one flat, kW/flat.

Alternative 3

The estimated electric load of the dwelling houses of a microdistrict (street block), which is applied to the 0.4 kV busbars of a transformer substation, is tentatively calculated as follows [17]:

$$P_{rat.dwel.h.} = P_{specif.dwel.h.} S_{micr.} 10^{-3} , \tag{2.3}$$

where $P_{specif.dwel.h.}$ is the specific estimated load of the household buildings, W/m^2; $S_{micr.}$ is the total area of the dwelling houses of the microdistrict (street block), m^2 .

Alternative 4

The estimated load depends on the installed load of the dwelling house, taking into account the load maximum simultaneity coefficient:

$$P_{rat.dwel.h.} = P_{inst.dwel.h.} k_{sim.c.fl.} , \tag{2.4}$$

where $P_{inst.dwel.h.}$ is the installed load of the dwelling house, kW; $k_{sim.c.fl.}$ is the load maximum simultaneity coefficient depending on the number of flats in the dwelling house under consideration.

The estimated electric load of public buildings have to be adopted based on the designs of the electric equipment at these buildings; for industrial buildings, based on the enterprise power supply designs or corresponding analogues.

The estimated load of a public building can be determined in the following way [20–22]:

$$P_{pub.} = k_{sim.c.pub} \Sigma P_{inst.pub.} , \tag{2.5}$$

where $k_{sim.c.pub}$ is the load maximum simultaneity coefficient; $P_{inst.pub.}$ is the installed capacity of the public building of one type, kW (determined according to the design conditions).

In accordance with the above, the estimated electric load of the public buildings and the residential buildings (with mixed consumers) within a microdistrict of the city, up to 1 kV, can be calculated by the following expression [20]:

Alternative 1

$$P_{0.4kV,L} = P_{buil.\max} + \sum_{1}^{n} k_{sim.c.,i} P_{other.buil.,i} , \tag{2.6}$$

where $P_{buil.max}$ is the maximum building load of all the buildings that are supplied from the line, kW; $P_{other.buil.,i}$ stands for the estimated load of other buildings that are supplied from the line, kW; $k_{sim.c.,i}$ is the load maximum simultaneity coefficient for public or dwelling buildings.

Alternative 2

The summary estimated electric load of a microdistrict (street block) that is applied to the 0.4 kV busbars of the transformer substation is calculated by the following formula [20]:

$$P_{0.4kV,TS} = (P_{spec.dwel.h.} + P_{spec.pub.})S_{micr.}10^{-3}, \tag{2.7}$$

where $P_{spec.pub.}$ is the specific load of the public buildings of the microdistrict, which is adopted for houses with electric stoves – 2.6 W/m^2, for houses with stoves with solid or gaseous fuel – 2.3 W/m^2.

The load of the 10...20 kV distribution network

The estimated electric load of the 10...20 kV city networks are determined by multiplying the sum of the estimated loads of individual transformer stations by a coefficient that accounts for the simultaneity of their load maximums:

$$P_{10-20kV,TS} = k_{sim.c.,10-20} \sum_{i}^{n_{TS,10-20}} P_{TS,i} \tag{2.8}$$

where $P_{TS,i}$ is the summary estimated active capacity of the 10-20/0.4 kV substations, which is connected to the network element under consideration, kW; $k_{sim.c.,10-20}$ – the load maximum simultaneity coefficient for the 10-20/0.4 kV transformers connected to the network element under consideration, depending on the number of transformer stations.

2.1.2. The specified method of load density

The total summary load of the city can be determined as follows:

$$S_{city} = \sigma_{av} \Pi_{city} = \sigma_{av} \sum_{i=1}^{n_{TS}} \Pi_{TS,i} , \tag{2.9}$$

where σ_{av} is the average load density in the city, MVA/km^2; Π_{city} is the size of the city built-up area and closely connected surrounding territory, km^2; $\Pi_{TS,i}$ is the service area of the i-th substation, km^2; n_{TS} is the number of transformer substations.

From the equality condition, it follows that

$$\sigma_{av} = \frac{k_{sim.c,TS} \sum_{i=1}^{n_{TS}} S_{TS,i}}{\sum_{i=1}^{n_{TS}} \Pi_{TS,i}} = \frac{k_{sim.c.,TS} \sum_{i=1}^{n_{TS}} n_i \beta_i S_{rat,i}}{\sum_{i=1}^{n_{TS}} \Pi_{TS,i}} , \tag{2.10}$$

where β_i is transformer load factor; $S_{rat,i}$ is rated capacity of transformer, MVA.

Load densities in some areas of the city, city districts and substation service areas tend to differ quite significantly from the average load density in the city depending on the type of development of the area, building floor number, household electrification level, consumer connection points. In case the load densities in transformer substations service area vary considerably, the average load density urban built-up area can be determined as follows:

$$\sigma_{av.city} = \frac{k_{sim.c.,TS} \cdot \left(S_{TS\,1} + S_{TS\,2} + \ldots + S_{TS,i}\right)}{\Pi_{TA\,1} + \Pi_{TA\,2} + \ldots + \Pi_{TA,i}} = \frac{k_{sim.c.,TS} \sum_{i=1}^{n_{TS}} S_{TS,i}}{\sum_{i=1}^{n_{TS}} \Pi_{TS,i}} = \frac{k_{sim.c.,TS} \sum_{i=1}^{n_{TS}} n_i \, \beta_i \, S_{rat,i}}{\sum_{i=1}^{n_{TS}} \Pi_{TS,i}}. \qquad (2.11)$$

Load density is the most important indicator in this method as well as in the determination of the loads of electric networks on the whole, yet data is lacking regarding the load densities in individual districts and transformer substation service areas in the city of Riga. Load density is a parameter that varies in time as the transformer substation loads increase or decrease. Therefore, the Thesis performs more precise definition of the load density in individual districts and microdistricts of the city of Riga, since the method of determining the load of transformer substations based on the average load density and the area of built-up territory will be used extensively at the further stages of the study [4, 16–18].

2.2. Load and energy price forecasting methods

A development facility has to solve long-term or medium-term designing tasks. For such a period, the solution of the tasks lacks precise initial information and detailed development of the facilities. In the tasks of development of the estimated loads of a city or its districts, it is only possible to use load forecasting or calculation methods on the basis of tentative, generalized indicators.

The most widely used forecasting methods are illustrated on Fig. 2.3.

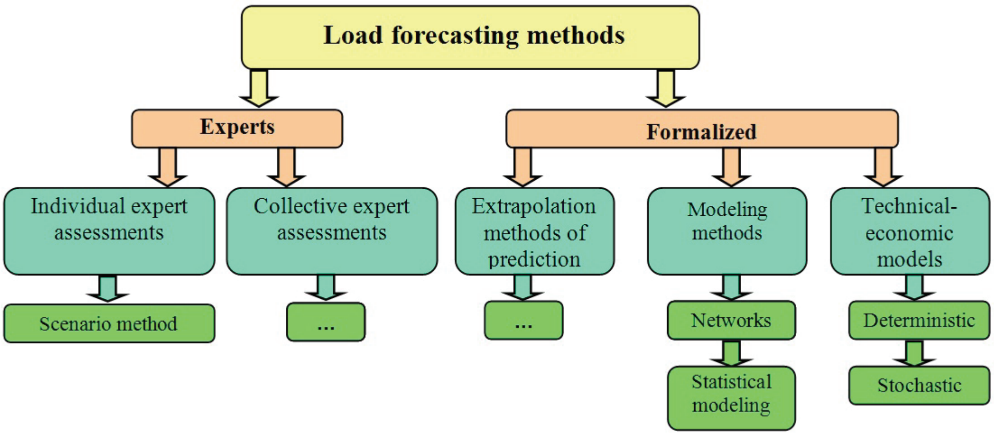


Fig. 2.3. Urban electrical loads forecasting methods

Below are described the new methods developed in recent years [24, 25] and offered examples of calculations.

2.2.1. Load forecasting example, using scenario method

The Thesis uses the scenario method for forecasting loads. It also has to be pointed out that the forecasting needs to be done in the conditions of information uncertainty and the obtained results have a tentative and recommendatory character.

The Thesis presents three electric power consumption forecast scenarios for Latvia and Riga in the period from 2014 till 2030: the pessimistic scenario (with an annual load increase of 1 %), the conservative scenario (with an annual load increase of 2 %) and the optimistic one (with an annual load increase of 3 %). These forecasts are shown on Fig. 2.4.

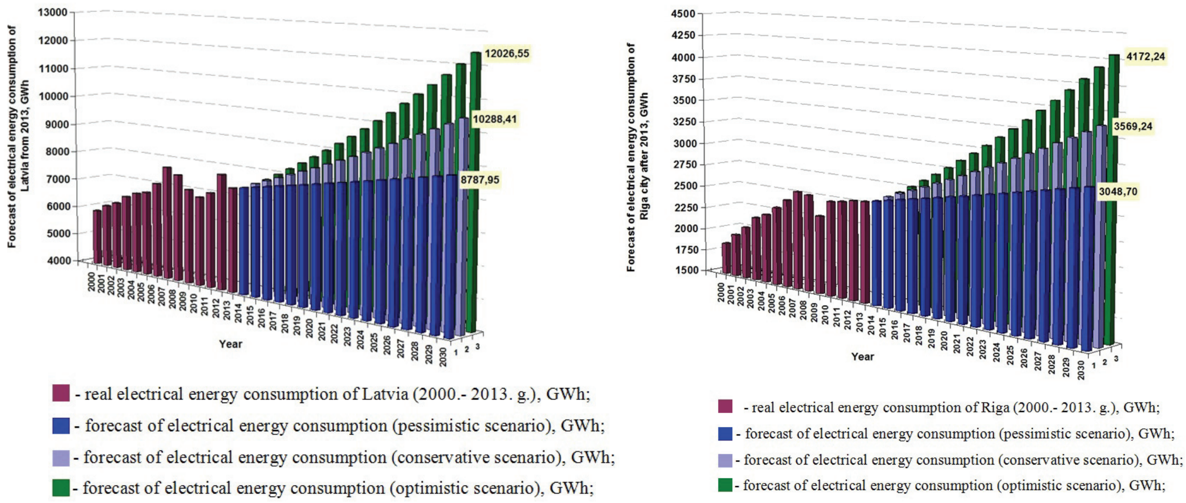


Fig. 2.4. The forecast 2013–2030 of electrical energy consumption in Latvia and Riga

After stabilization of the economic situation, the indicator change curves and increase trends can be determined more precisely.

2.2.2. Load forecasting example, using the neural network method

In the recent decades, along with the development of artificial intelligence, it has been offered to solve load forecasting problems by using models based on artificial neural networks. A subchapter of the Thesis gives a brief description of a neural network model, which has been developed by means of MATLAB® software [23, 26]. The result is shown on Fig. 2.5.

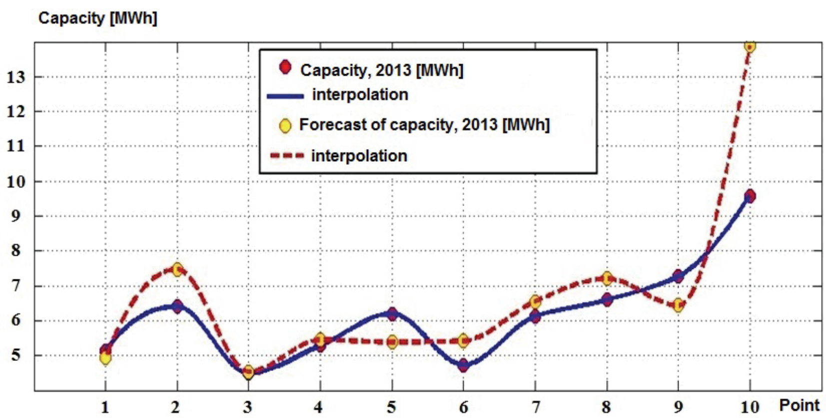


Fig. 2.5. The capacity in 2013 and its forecasting, using the neural network method

2.2.3. Energy price forecasting example, using the neural network method

This section focuses on long-term energy price forecasting using neural networks (NN) method. Prediction accuracy is significantly dependents on the structure of the neural network (the neural network type and quantity of neurons). A deep analysis of the structure of the NN is done.

For network training is used 2014 year data. Energy prices forecast is made on May 16 (the day is picked randomly). The result is shown in Fig. 2.6.

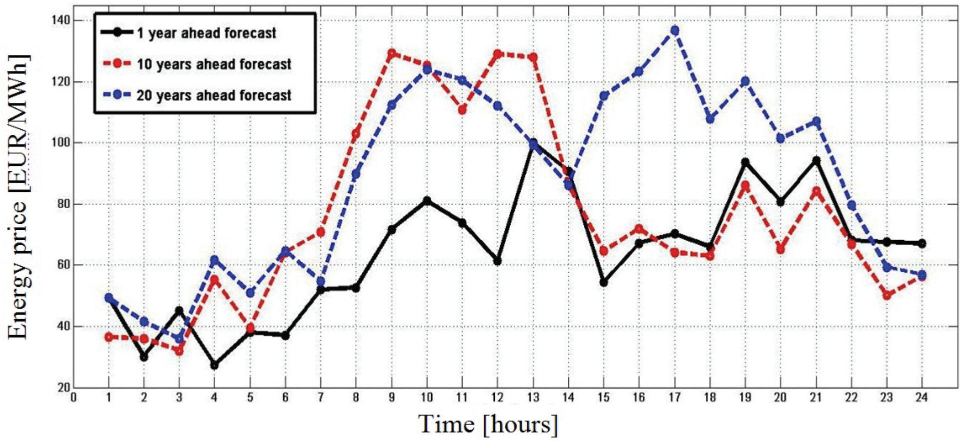


Fig.2.6. Energy price forecast depending on time of day

It is necessary to note that the NN use for energy price forecasting is based on past statistics. Furthermore trained NN has a memory. Using this method can accurately predict as the city electrical load, as energy prices.

An advantage in forecasting by means of an instructed neural network is the relatively easy instruction and its future use.

3. LOAD DENSITY ANALYSIS IN THE TERRITORY OF RIGA

3.1. The theoretical basis of the formation of the substations load density

Chapter three discusses the issue related to the determination of the prospective loads of transformer substations (TS) of various voltage levels based on load densities. Load density is an important indicator for determining the load of the microdistricts of Riga and of cities as well as for choosing the parameters of elements. Information about load density values of Riga city are not systematic and are not sufficient for urban development problem solving. Therefore, in this section determination and clarification of this parameter is done.

When setting up a hierarchy of load density in accordance with the hierarchy of voltages, the actual load densities for each voltage level are different. This can be seen from the expressions in Table 3.1.

Table 3.1

The load density value at each voltage level

	0.4 kV	10-20 kV	110 kV	330 kV
0.4 kV	$\sigma_{0.4} = \dfrac{S_{\Sigma 0.4}}{\sum \Pi_{0.4}}$	$\sigma_{10-20} = k_{v,10-20} \cdot \sigma_{0.4}$	$\sigma_{110} = k_{v,10-20} \cdot k_{v,110} \cdot \sigma_{0.4}$	$\sigma_{330} = k_{v,10-20} \cdot k_{v,110} \cdot k_{v,330} \cdot \sigma_{0.4}$
10-20 kV		$\sigma_{10-20} = \dfrac{S_{\Sigma 10-20}}{\sum \Pi_{10-20}}$	$\sigma_{110} = k_{v,110} \cdot \sigma_{10-20}$	$\sigma_{330} = k_{v,10-20} \cdot k_{v,110} \cdot \sigma_{10-20}$
110 kV			$\sigma_{110} = \dfrac{S_{\Sigma 110}}{\sum \Pi_{110}}$	$\sigma_{330} = k_{v,330} \cdot \sigma_{110}$
330 kV				$\sigma_{330} = \dfrac{S_{\Sigma 330}}{\sum \Pi_{330}}$

where $S_{\Sigma 0.4}$ is the total load of the consumers at the 0.4 kV stage, MVA ; $S_{\Sigma 10-20}$ is the total load of the consumers at the 10-20 kV stage, MVA; $S_{\Sigma 110}$ is the total load of the consumers at the 110 kV stage, MVA; $S_{\Sigma 330}$ is the total load of the consumers at the 330 kV stage, MVA; $\sum \Pi_{0.4}$ is the total service area of the consumers at the 0.4 kV stage, km^2; $\sum \Pi_{10-20}$ is the total service area of the consumers at the 10-20 kV stage, km^2; $\sum \Pi_{110}$ is the total service area of the consumers at the 110 kV stage, km^2; $\sum \Pi_{330}$ is the total service area of the consumers at the 330 kV stage, km^2; $k_{V,10-20}$ is the load maximum simultaneity coefficient of the 10-20/0.4 kV transformer loads depending on the number of 10-20 kV TS; $k_{V,110}$ is the load maximum simultaneity coefficient of the 110/10-20 kV transformer loads, depending on the number of 110 kV TS; $k_{v,330}$ is the load maximum simultaneity coefficient of the 330/110 kV transformer loads depending on the number of 330 kV TS.

In this Chapter of the Thesis, special attention is paid to individual power supply systems: the 0.4 kV and the 10-20 kV systems.

There is a distribution of consumers among the substations, which determines the current service areas of the substations. It is difficult to analyze the changes in load density as the service area of a TS changes. Therefore, to ensure a unified approach to the distribution of transformers in the territory of the city, the unified methodology for modeling the substation service areas has been used [16, 18, 19].

3.2. Adjustment of the substations service areas and load density

This subsection adjusts, calculates and analyzes the distribution of the service areas of the 110 kV substations in the city of Riga, based on the data of JSC "Latvenergo" and the distribution map of the actual TS service areas [16, 17] and taking into account the non-useful service areas of transformer substations (rivers, lakes, forests, canals, etc.). "Nature elements" cannot be taken into account in calculations since that can lead to incorrect decisions in defining the load density of a district.

Taking into account calculations of useful load density values, load density distribution for 110 kV TS is offered. These calculations have been performed for the year 2010, since information regarding other years is not available.

Given the useful service area and capacity values, it is possible to calculate the useful load density for each substation:

$$\sigma_{useful} = \frac{S_{TS}}{\Pi_{TS} - \Pi_{useless}} = \frac{S_{TS}}{\Pi_{useful}} , \qquad (3.1)$$

where σ_{useful} is the load density in service area of TS, MVA/km^2; S_{TS} is the total electrical load of TS, MVA; Π_{TS} is the total service area of TS, km^2; $\Pi_{useless}$ is the useless service area of TS, km^2; Π_{useful} is the useful service area of TS, km^2.

At different load densities in the transformer substation service areas, the average load density within the city is defined as follows:

$$\sigma_{av.useful} = \frac{\sigma_1\Pi_1 + \sigma_2\Pi_2 + ...\sigma_i\Pi_i}{\Pi_{useful}}, \tag{3.2}$$

where $\Pi_1,...,\Pi_i$ is the service area of the i-th city district, km^2.

Expression (3.2) enables an adjustment in the load density of a city or a city district in the case of changes in the TS load or the built-up territory at any level of the hierarchy. If the city built-up territory and other territory closely related to it and adjoining territory enlarges by new territories that have not been used for buildings up to the moment, then the boundaries of the built-up territory of the city change and the load density can be calculated in the following way:

$$\sigma'_{useful} = \frac{\sigma_1(\Pi_1 + \Delta\Pi_1) + \sigma_2(\Pi_2 + \Delta\Pi_2) + ... + \sigma_i(\Pi_i + \Delta\Pi_i)}{\Pi_{useful}}, \tag{3.3}$$

where $\Delta\Pi_1,...,\Delta\Pi_i$ is the change in the service are of the i-th city district, km^2.

If the summary load of a city district or microdistrict increases then the load density can be reflected as follows:

$$\sigma''_{useful} = \frac{k_V((S_{TS,1} + \Delta S_{TS,1}) + (S_{TS,2} + \Delta S_{TS,2}) + (S_{TS,i} + \Delta S_{TS,i}))}{\Pi_{useful}}, \tag{3.3}$$

where $\Delta S_{TS1}, \ldots, \Delta S_{TS,i}$ is the change in the summary load of the i-th city district, MVA.

The above-mentioned parameters make it possible to determine the parameters of the maximum pattern of the hexagon model at a corresponding useful load coefficient:

$$\Pi_{permis,i,t} = \frac{n_{T,i}\beta_{permis,i,}S_{rat,i}}{\sigma_{useful}}$$

$$R_{permis,i,t} = 0.62\sqrt{\frac{n_{T,i}\beta_{permis,i}S_{rat,i}}{\sigma_{permis,i,t}}}, \tag{3.4}$$

where $\Pi_{permis,i,t}$ is the service area of the i-th transformer substation; $R_{permis,i,t}$ is the permissible radius of the service area of the i-th substation, km^2; $\beta_{permis,i}$ is the permissible load coefficient of the i-th substation; $n_{T,i}$ is the number of transformers of the i-th substation.

The full load coefficient has been calculated and compared with the permissible value:

$$\beta_{full,i} = \frac{S_{TS}}{n_{T,i}S_{rat,i,}} \tag{3.5}$$

Considering the above, an algorithm for adjusting the load density in the network of Riga city is developed, which is shown on Fig. 3.1.

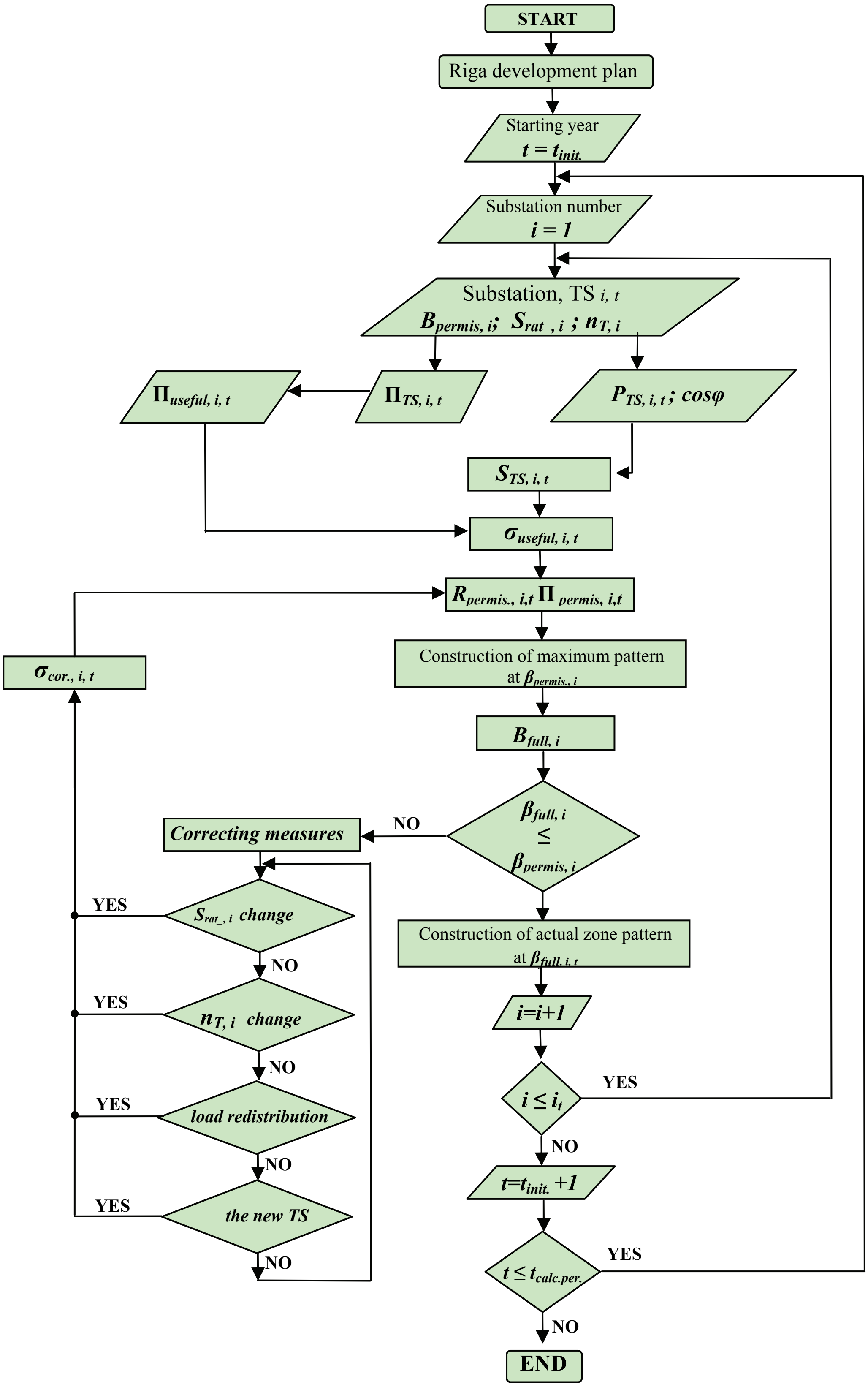


Fig. 3.1. The load density correction algorithm in development projects

3.3. Formation of load density cartograms for city districts (microdistricts)

The load density in future city districts or microdistricts can be calculated, if the total loads and areas of districts (microdistricts) are known, or can be assumed analogically to load density in typical districts with buildings of the corresponding number of storeys. For determining the approximate total loads in new districts (microdistricts) at initial design stages, an approximate method can be used, which is based on average load densities [25].

The information about the load density values of Riga city is not systemized and is not sufficient for solving the city development tasks. Therefore in this Thesis, these indicators are determined and made more precise. It should be noted that the load density values are different in the city as a whole and in separate TA service areas.

This Chapter presents a calculation of loads and load density of several separate subdistricts (blocks) of Riga city districts, taking into account simultaneity coefficients and voltage hierarchy. Also, a load density cartogram for these subdistricts is formed.

As a result of the performed analysis, a united load density classification is proposed for zones with different number of storeys in buildings.

For conducting the research, the programs ArcGIS, Excel and AutoCAD are used.

3.3.1. Formation of load density cartogram for microdistrict “Imanta”

This subsection analyzes the microdistrict “Imanta”, its built-up territory, the number of storeys of the existing buildings, the installed electrical load of each house (the data of “Latvenergo”) and the load densities. A correction of the number of storeys plan of “Imanta” is proposed, which changes a concept of the load density value to a considerable extent.

More than 400 objects are considered in the research. According to detailed studies of the microdistrict “Imanta” and using the ArcGIS software, it has been concluded that the building number of storeys plan, according to the development plan, has become out-of-date and needs to be corrected due to the nonexistent territory of dwelling houses and unconformity in the number of storeys. Hence, a correction of the division of the real area of substation “Imanta” into subdistricts according to the number of storeys is proposed. The microdistrict “Imanta” is divided into 40 zones (subdistricts). Taking into account the load data, the values of useful service areas as well as the value of the simultaneity coefficients for summing up the loads, a load density of each zone is calculated. The results are shown on Fig. 3.2.

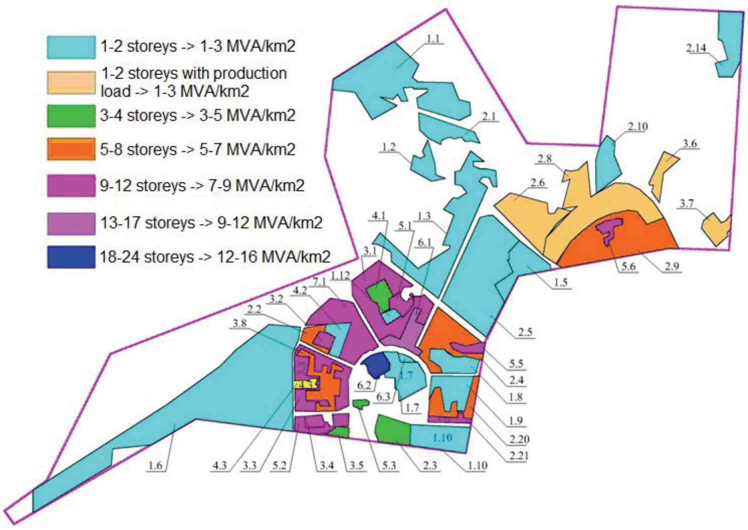


Fig. 3.2. Correction of the division of the real area of substation “Imanta” into zones according to the number of storeys

According to the obtained results, the average load density of the district "Imanta" is determined: $\sigma_{vid.raj,0.4} = 4,6$ (MVA/km^2). The calculations of the approximate calculated load density of the district "Imanta" are performed on the basis of the number and area of storeys (Table 3.2.).

Table 3.2.

The approximate estimated load densities of district "Imanta" based on the number and area of storeys

Type of buildings, number of storeys	П, km^2	District load density σ, MVA/km^2		
1÷2	5,52	1,0	–	3,0
3÷4	0,227	3,0	–	6,5
5÷8	1,746	6,5	–	8,0
9÷12	1,35	8,0	–	9,0
13÷17	0,09	9,0	–	12,0
18÷24	0,065	12,0	–	16,0

Knowing the load density at the low voltage level and using the expressions in Table 3.1., the load densities at all the voltage levels are calculated. The simultaneity coefficient values are taken from [16].

$$\sigma_{10-20} = k_{sim.c.,10-20}\sigma_{0,4} = 0,85 \cdot 4,6 = 3,91 \text{ (MVA/km}^2\text{)},$$

$$\sigma_{110} = k_{sim.c.,110}\sigma_{10-20} = k_{sim.c,10-20}k_{sim.c.,110}\sigma_{0,4} = 0,85 \cdot 0,90 \cdot 4,6 = 0,76 \cdot 4,6 = 3,52 \text{ (MVA/km}^2\text{)},$$

$$\sigma_{330} = k_{sim.c.,330}\sigma_{110} = k_{sim.c.,10-20}k_{sim.c.,110}k_{sim.c.,330}\sigma_{0,4} = 0,85 \cdot 0,90 \cdot 0,95 \cdot 4,6 = 3,30 \text{ (MVA/km}^2\text{)}$$

Load density of district "Imanta" at 110 kV voltage level is 1.62 MVA/km^2. Compared to getting result (3.91 MVA/km^2), it is resulted that results are different. This can explain, firstly, the fact that the calculations were made for different years. Secondly, useful service areas are different. After detailed analysis of build-up area, is concluded that the Development Plan map is outdated and should be completed.

3.3.2. Formation of load density cartogram for microdistricts powered by the substation "Zunda"

In compliance with the Riga City Development Masterplan [11], in the nearest future, it is planned to build a number of large and significant buildings in the area of TA "Zunda" location. Taking into account rapid development of this part of Riga, the load of the substation will reach the installed capacity of the transformers – 2 × 25 (MVA).

Taking into account the map of the Development Masterplan [11, 16] and the existence of useless areas, a modified map showing the division into 50 zones (city blocks) is worked out, which gives a clear concept of the number of storeys in each zone (Fig. 3.3.).

On the basis of the theoretical justification provided in Chapter two, estimated loads for each zone are calculated.

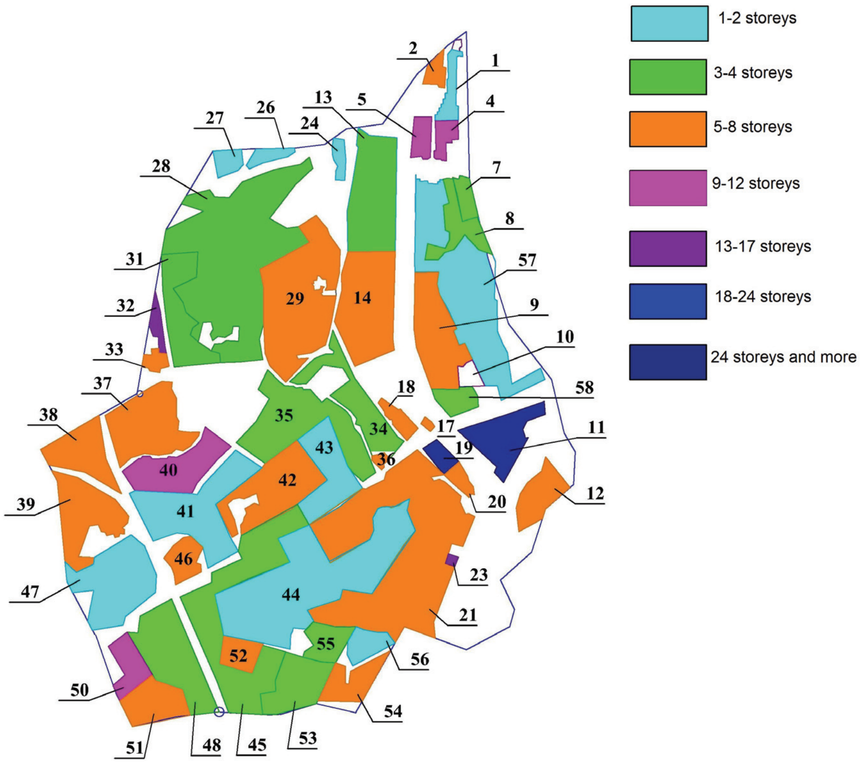


Fig. 3.3. The map of substation "Zunda" service area with 50 city blocks according to the number of storeys

Taking into account the obtained results, the calculations of the approximate estimated load densities for the microdistrict "Zunda" according to the number and area of storeys are presented (Table 3.3.).

Table 3.3.

The approximate estimated load densities for the district "Zunda" according to the number and area of storeys

Type of buildings, number of storeys	П, km^2	District load density σ, MVA/km^2
1÷2	1,034	1,0–2,0
3÷4	1,633	2,0–6,0
5÷8	1,8884	6,0–9,0
9÷12	0,168	9,0–12,0
13÷17	0,0202	12,0–17,0
18÷21	0,052	17,0–20,0
21÷26	0,050	20,0–25,0

Knowing the average value of load density at the low voltage level (σ = 5,38 MVA/km^2) and using the expressions in Table 3.1., the load densities at all the voltage levels are calculated:

$$\sigma_{10-20} = 4{,}57 \text{ (MVA/km}^2\text{)}, \quad \sigma_{110} = 4{,}10 \text{ (MVA/km}^2\text{)}, \quad \sigma_{330} = 3{,}87 \text{ (MVA/km}^2\text{)}.$$

In the district "Zunda", the load density at the 110 kV voltage level is 5,23 MVA/km^2. Comparing with our obtained result (4,57 MVA/km^2), it can be concluded that the data are different (12 %). This can be explained by the following: when the district "Zunda" being developed, the service area has increased.

Approximate load densities are determined for individual sectors of the city and summarized in Table 3.4. [8, 16, 27, 28].

Table 3.4.

Approximate load density in the sectors of the city of Riga

District	Storey number	Load density (on 10,5 kV busbars), MVA/km^2
Old Town	3–6	36,8
Plavnieki	9	8,4
Mezciems	9	7,4
Ziepniekkalns	9–12	7
Zakusala	2; 3; 5; 7–9; 18–24; 25	5,2–5,7
Lucavsala	7–9; 18–24	10,82–14,11
Rumbala	3, 7–9; 18–24	5,6–6,8
Imanta	1; 2; 5; 9–12; 16; 26	3,91
Zunda (Kipsala, Kliversala, part of Pardaugava)	5; 6; 9–12	4,57

4. METHODS OF CHOOSING THE OPTIMUM CROSS-SECTIONS OF ELECTRICAL LINES UNDER MARKET ECONOMY CONDITIONS

The economic efficiency of construction and operation of an electric power system depends on rational arrangement of electrical networks. Up to 15 % of electricity is lost in the elements of electrical networks; furthermore, losses in overhead line wires, cables and transformer windings due to heating-up constitute the main part of these losses, which occur due to the presence of the active resistance in lines and transformers.

A specific radical way how to reduce this part of the total losses might be decreasing the active resistance of conductor or cable cores. It is possible to reduce the active resistance only by increasing the cross-section of conductor or cable cores. From the other hand, the increase of the cross-section is connected with rise in price and increase of annual costs of power transmission lines.

Hence, the choice of the optimum cross-section of conductors and cables at the design stage or in case of network reconstruction is one of the basic conditions that largely determine further costs of arranging the network.

4.1. A review of the economic current density method and the economic intervals method

The choice can be determined by the economic current density method or the economic intervals method. Both methods are based on the annual costs minimum criterion; however, they differ by the calculation accuracy [29–32].

Depending on the current, the annual costs of the line with various cross-sections can be determined in the following way:

$$C_i = (i + p_\Sigma)(a + b \cdot F)l + 3I_{max}^2 (\tau\beta' + \beta'')\frac{l}{\gamma F}10^{-3} \quad , \tag{4.1}$$

or

$$C_i = (i + p_\Sigma)K_{CL} + 3I_{max}^2 R(\tau \cdot \beta' + \beta'')10^{-3} \tag{4.2}$$

where i is the market interest rate, r.u.; p_Σ are the total deductions on amortization, running repair and maintenance from the capital investments in cable line, r.u.; γ – the specific conductivity, m/Ω*mm^2 ; a – the line fixed costs component, not depending on the cross-section, €/km, (foe example, the costs of route preparation works, the costs of constructing access roads, etc.); b – the coefficient, which is proportional to the cross-section area, or the rise-in-price coefficient, which indicates the change of the line cost when the cross-section changes by 1 mm^2, €/km*mm^2; K_{CL} are the capital investments in the line with wire of standard cross-section, €; I_{max} is the maximum load current of line, A; R is active resistance for standard cross-section, Ω/km; τ is the utilization time of maximum losses per year, where $\tau = f(T_{max})$, h; T_{max} is the utilization time of maximum load per year, h; β' is the specific price of electric power losses, €/kWh; β'' is the specific price of capacity at the maximum time of power system load, €/kW.

After a detailed analysis, it is concluded that the choice of conductors and cables by the economic current density method does not allow obtaining the annual cost minimum, because the method has certain assumptions and inaccuracies. Hence, the economic intervals method has been researched [29, 30]. The annual total cost equality condition for standard cross-sections of adjacent conductors is assumed as the base of the method:

$$C_i = C_{i+1} \, . \tag{4.3}$$

Taking into account the condition (4.3) and the expression (4.2), a sustaining current is determined, at which the conversion from a smaller cross-section to a larger one is economically feasible [30]:

$$I_{econ} = \sqrt{\frac{(i + p_\Sigma)}{\tau\beta' + \beta''}}\sqrt{\frac{(K_{CL(i+1)} - K_{CLi})10^3}{3(R_i - R_{i+1})}} = \sqrt{\sigma}\sqrt{\frac{(K_{CL(i+1)} - K_{CLi})10^3}{3(R_i - R_{(i+1)})}} \, , \tag{4.4}$$

where $\sigma = \frac{(i + p_\Sigma)}{\tau \cdot \beta' + \beta''}$ – the factor that depends on the technical and technical-and-economic parameters of the network.

According to this method, it is possible to construct universal economic nomograms, which ensure the more precise and convenient choice of the economic cross-section for various voltage levels and network designs, as compared with the economic current density method [29, 30].

The economic intervals method has been theoretically deepened and developed in the research works [1, 29, 31, 33–35].

Based on this methodology, an idea of capacity intervals has been reflected in various published works [30, 34].

4.2. Modification of the economic intervals method

The conversion to market relations in the economy required the decision-making methodology to be reviewed in the sphere of investment policy in all branches of industry, including the electric power industry. This resulted in significant changes in the substantiation of cost-effective construction projects of overhead and cable lines. These changes are mainly related to the availability of information regarding the cost of construction of 1 kilometer of overhead and cable power transmission line, the cost of equipment and construction and installation work.

In the market economy conditions, the investments in the construction of energy facilities determine the own capital of power companies, the interests and financial possibilities of investors. In many countries, the mentioned conversion led to unavailability of unified summarizing indicators of the line value. It complicates the variants assessment process, since it takes place in conditions of uncertain initial information.

As a result of the mentioned changes, it has been found that the value of capital investments is determined by the market of electrical materials and construction and installation works. Hence, in conditions of shortage of funds in the energy sphere, the projects should be technically and economically justified and efficient.

In spite of the advantages of the economic intervals method, it still does not work to a full extent under the market economy conditions. Hence, in the present-day economic conditions, the traditional methods of choosing the cross-sections of lines need critical analysis and certain correction.

In this regard, this Thesis proposes a modified approach for implementing the economic intervals method. This modification makes it possible to choose an economically feasible, rational cross-section and ensure minimum total costs both for construction and operation of electrical networks. The modification of this method is based on searching the minimum total cost of the construction of the line. By means of justified mathematical transformations, we have managed to exclude some constituent parts (the costs of construction and installation works for adjacent cross-sections) from the cost function, which are not unambiguously determined under the market economy conditions. As a result, the economic intervals have been calculated according to the current and capacity and nomograms thereof have been constructed.

4.2.1. Modification of the economic intervals method for overhead lines and construction of nomograms for rational choosing of cross-sections

Taking into account the modification of the method for market conditions, the economically feasible current is calculated as follows:

$$I_{ek,GL} = \sqrt{\frac{i + p_{\Sigma}}{\tau\beta' + \beta''}} \cdot \sqrt{\frac{n_f (K_{met,(i+1)} - K_{met,i})}{3(R_i - R_{i+1})10^{-3}}}, \tag{4.5}$$

where $K_{met,i}$, $K_{met,(i+1)}$ – the cost of metal of the line conductor for adjacent cross-sections, €; n_f – the number of phases in the line.

After various mathematical transformations, we obtain the economically feasible current and capacity values, at which the conversion from the smaller cross-section to the larger one is cost-effective:

$$I_{econ,OHL} = \sqrt{\sigma} \sqrt{\frac{n_f K_{0,met,GL} D_{met,OHL} (F_{i+1} - F_i)}{3(R_{0i} - R_{0,(i+1)})}}, \tag{4.6}$$

$$P_{econ,OHL} = U \cos\varphi \sqrt{\sigma} \sqrt{\frac{n_f K_{0,met,OHL} D_{met,OHL} (F_{i+1} - F_i)}{(R_{0i} - R_{0,(i+1)})}}, \tag{4.7}$$

where $K_{0,met}$ – the cost of 1 kg of conductor metal of the line, €/kg; $D_{met,OHL}$ – the density of conductor metal, kg/m^3; F_{i+1}, F_i – the adjacent cross-sections of the conductor, mm^2; R_{0i}, $R_{0,(i+1)}$ – the active resistance of the adjacent cross-section conductors, Ω/km, U – the nominal voltage of the line, kV; $\cos\varphi$ – the power factor.

The nomograms of the economic intervals current $I_{econ,OHL}=f(\sqrt{\sigma})$ and capacity $P_{econ,,OHL}=f(\sqrt{\sigma})$ are calculated and constructed for 0.4-10-20-110 kV three-phase overhead lines with aluminium, copper and steel-aluminium conductors with standard cross-sections: 4, 6, 10, 16, 25, 35, 50, 70, 95, 120, 150, 240, 300 mm^2, as well as the current nomograms for the 330 kV overhead lines with aluminium, copper and steel-aluminium conductors with split cross-sections: 2 × 240, 2 × 300, 2 × 400, 2 × 500, 2 × 600 mm^2 (see Fig. 4.1., 4.2.).

Also, the nomograms of the HTLS (High Temperature Low Sag Conductor) overhead line current are constructed (see Fig. 4.3.). HTLS type conductors are efficient, since they, firstly, are capable of long-term operation at high temperatures over 100 °C without losing wire tension strength, thus increasing the line transfer capability; secondly, these conductors have lesser sags at high temperatures, which allows observing all the necessary standard sizes to ground and objects to be crossed without elevating and reconstructing the support structure [36].

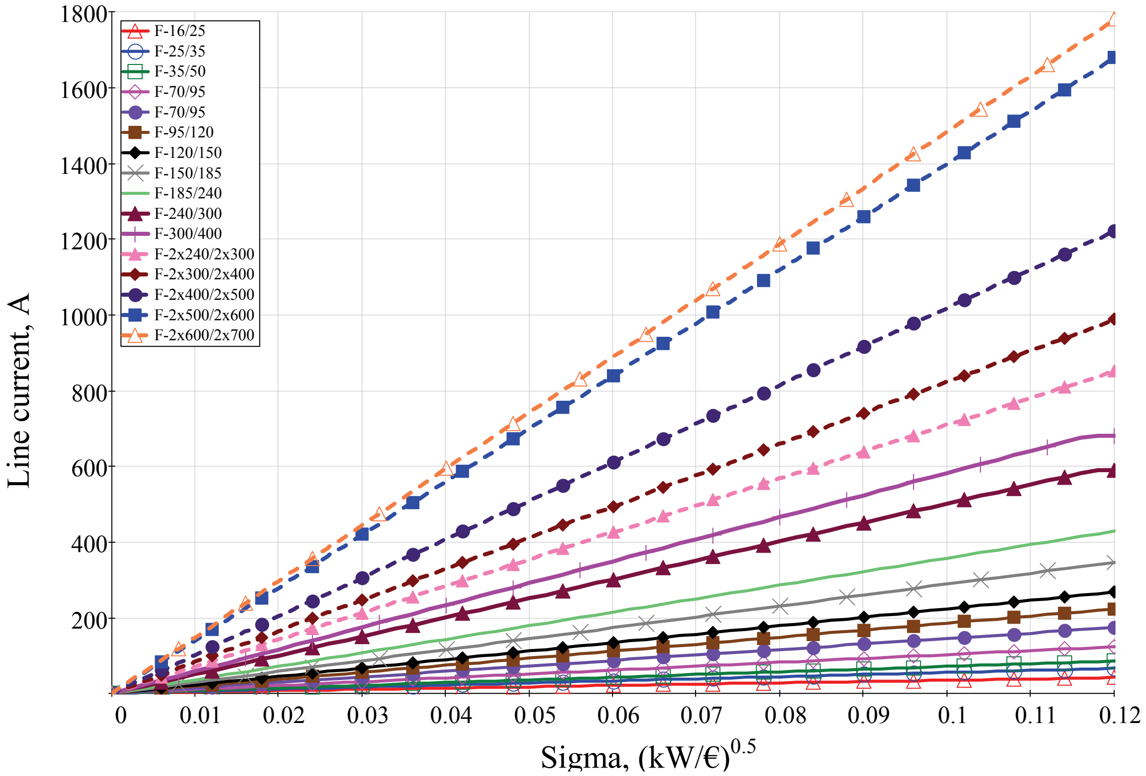


Fig. 4.1. Universal current nomograms for 0.4-10-20-110-330 kV overhead lines with aluminium conductor

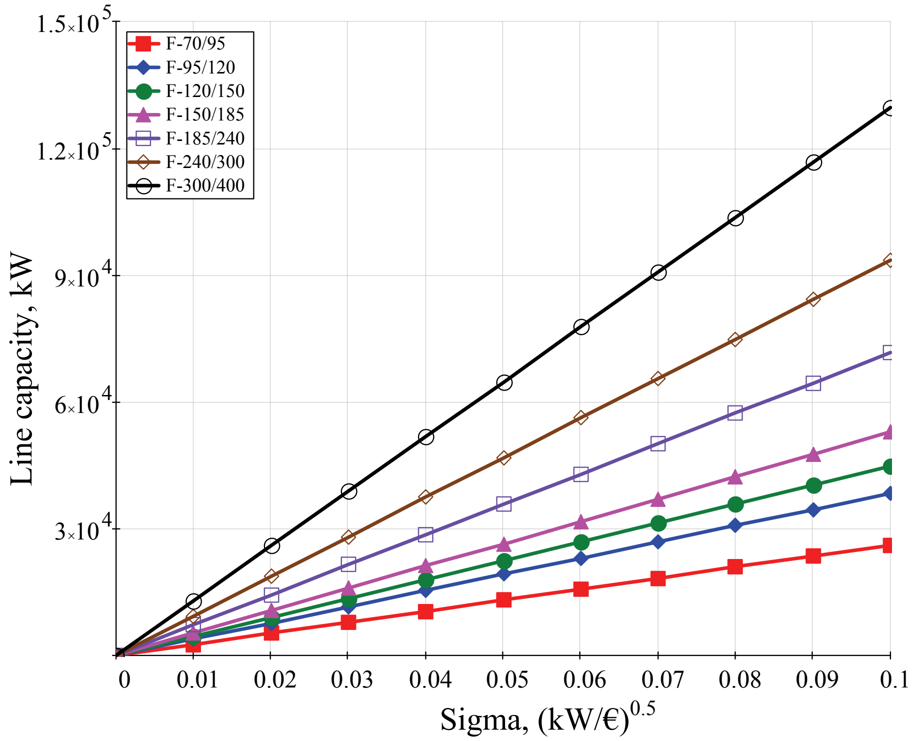


Fig. 4.2. Capacity nomograms for 110 kV overhead lines with steel-aluminium conductor

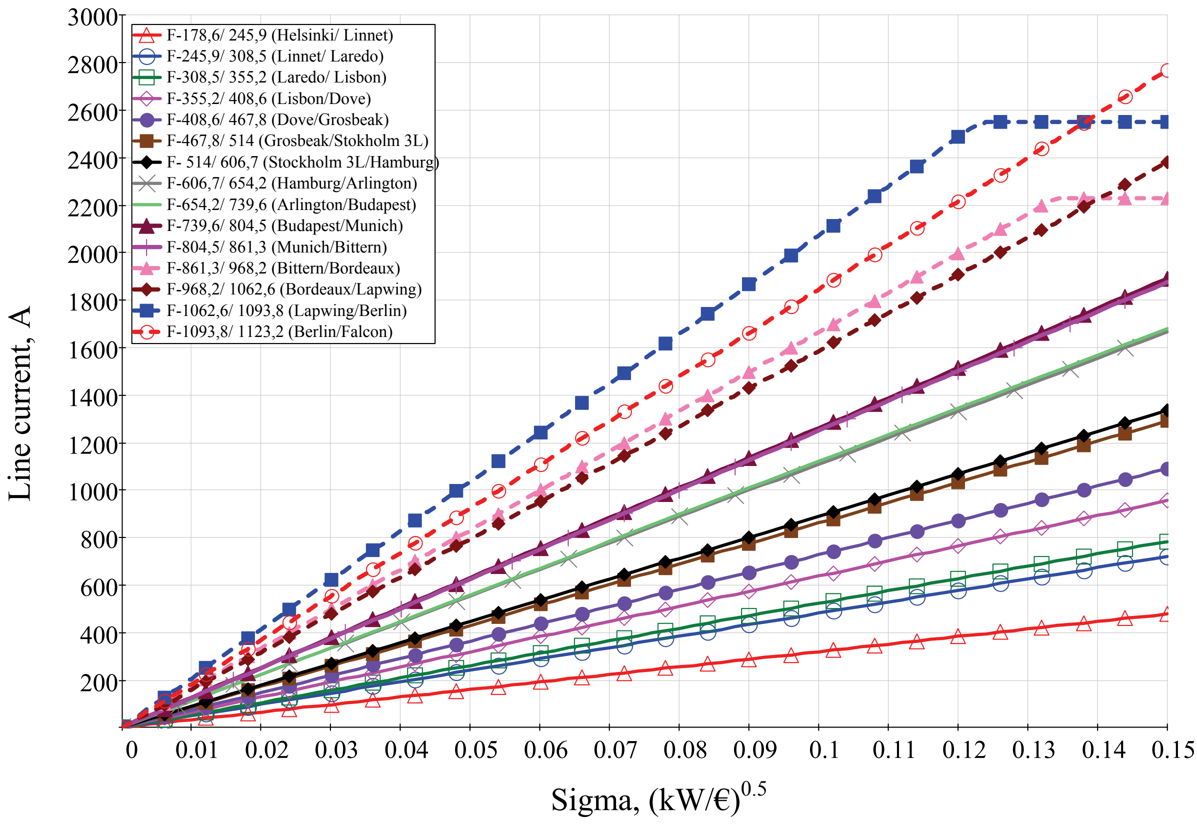


Fig. 4.3. 110 kV ACCC (Aluminium Conductor Composite Core) wire current nomograms

4.2.2. Modification of the economic intervals method for cable lines and construction of nomograms for rational choice of cross-sections

The research work proposes the correction of the economic intervals method for cable lines with cross-linked polyethylene (XLPE) insulation. The expressions of the economically feasible values of current and capacity are obtained [37–39]:

$$I_{econ,CL} = \sqrt{\sigma}\sqrt{\frac{A(F_{i+1}-F_i)+B(d_{core,(i+1)}-d_{core,i})}{3(R_{0,i}-R_{0,(i+1)})}}, \quad (4.8)$$

$$P_{econ,CL} = U\cos\varphi\sqrt{\sigma}\sqrt{\frac{A(F_{i+1}-F_i)+B(d_{core,(i+1)}-d_{core,i})}{3(R_{0,i}-R_{0,(i+1)})}}, \quad (4.9)$$

where $A = n_{core}K_{0,met,CL}D_{met,CL}\,K_1 K_2 K_{res}$

$B = \pi D_{isol,CL}\,K_5\,K_{0,isol,CL}S_{isol,CL}$

where n_{core} – the number of cores; $K_{0,met,CL}$ – the cost of 1 kg of cable metal, €/kg; $D_{met,CL}$ – the specific weight of core metal, kg/m^3; K_1 – core strand twisting coefficient; K_2 – cable, conductor, cord strand twisting coefficient; K_{res} – the reserve coefficient according to the minimal mass, which is determined by the technical or technological documentation developer, considering the peculiarities of products and their manufacture technology; $D_{isol,CL}$ – the specific weight of isolation, kg/m^3; K_5 – coefficient, considering technological factors (unevenness of applying, filling of empty places between wires); $K_{0,isol,CL}$ – the cost of 1 kg of cable isolation, €/kg; $S_{isol,CL}$ – the thickness of cable isolation, mm.

The current and capacity nomograms are calculated and constructed for single-core 0.4 kV, 10 kV, 20 kV, 110 kV and 330 kV XLPE cable line with aluminium and copper conductors (see Fig. 4.4., 4.5.). When constructing the nomograms, attention has been paid also to cable laying methods.

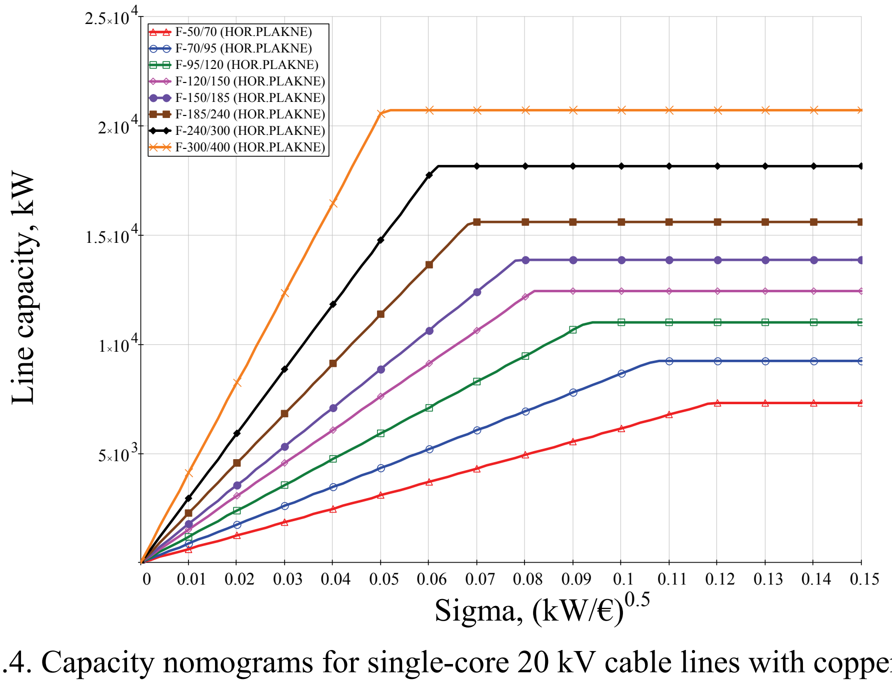


Fig. 4.4. Capacity nomograms for single-core 20 kV cable lines with copper conductors

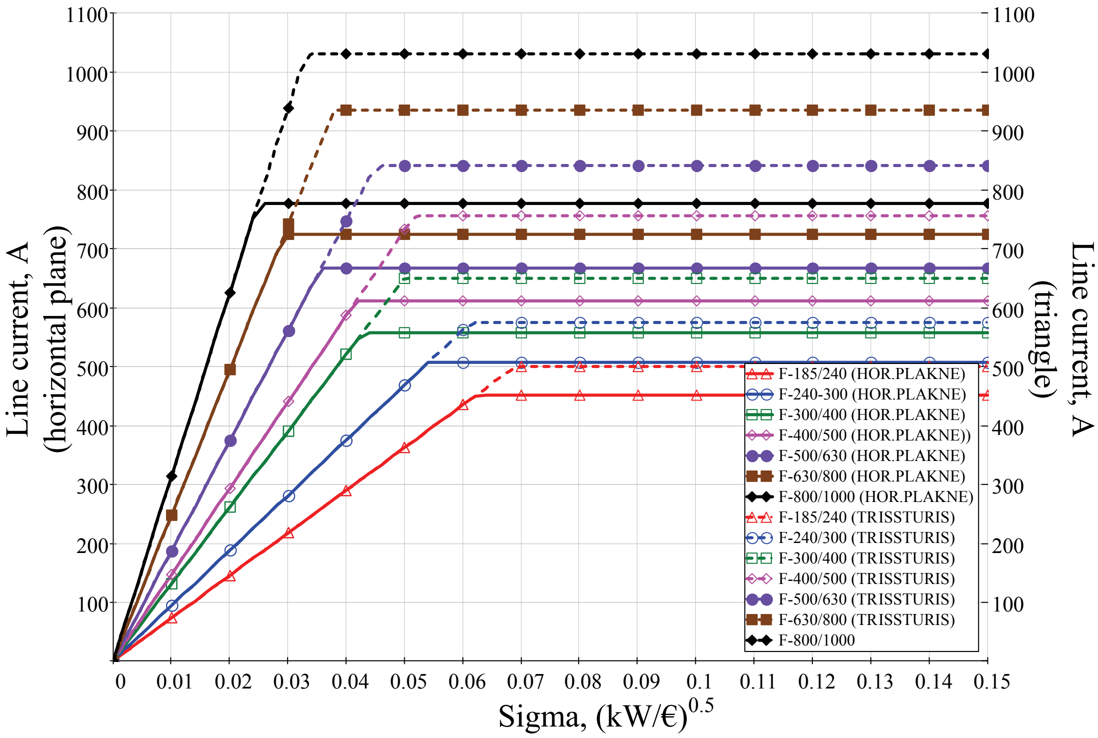


Fig. 4.5. Current nomograms for single-core 110 kV cable lines with copper conductors depending on cable laying method

4.3. Implementation of the economic intervals method in the Matlab environment

In this part of the Doctoral Thesis, the implementation of the modified economic intervals method for practical calculations is described. A graphical user interface is created in the Matlab programming environment (Fig. 4.6., 4.7.). With the help of this program, the optimum cross-section both for 0.4-10-20-110-330 kV overhead line and 0.4-10-20-110-330 kV cable line can be calculated [37, 38].

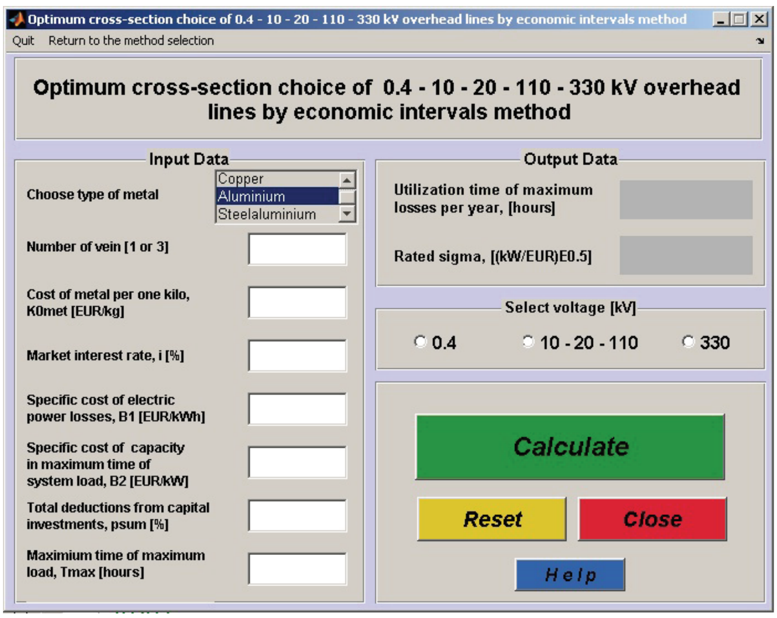


Fig. 4.6. Graphical user interface for overhead lines

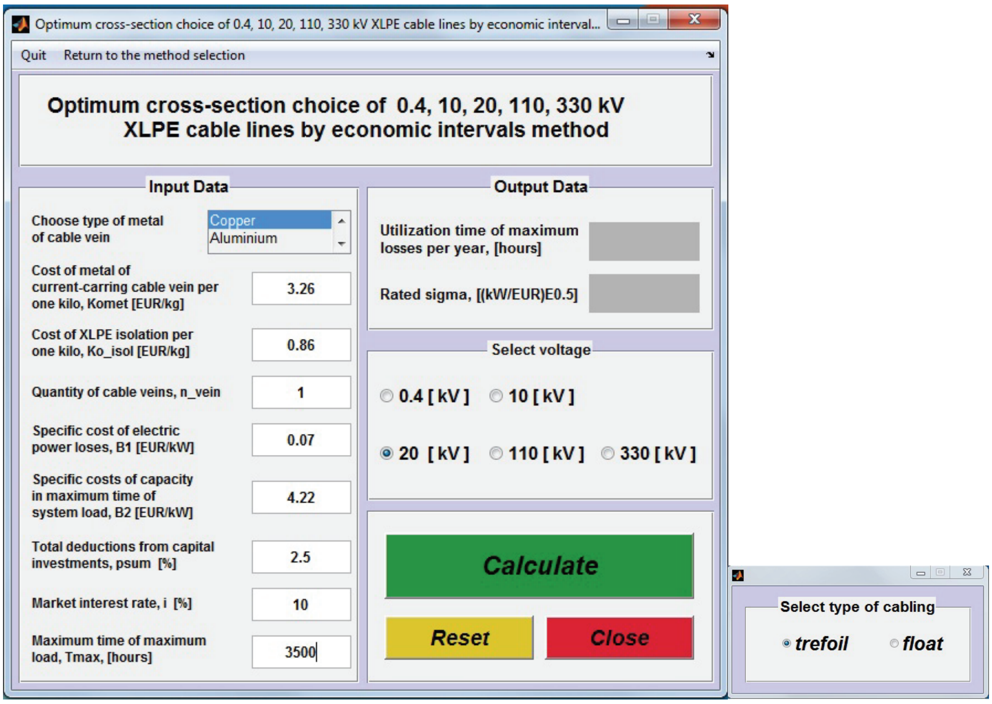


Fig. 4.7. Graphical user interface for cable lines

5. THE STOCHASTIC APPROACH FOR SELECTING HIGH-VOLTAGE LINE PARAMETERS

In recent years, power industries have faced considerable changes including deregulation, open markets, appearance of local generation and renewable generation sources. These factors significantly change the planning task and the solution conditions and inspire a search for a new, more adequate method. Therefore, it is necessary to carry out more adequate technical and economic calculations in order to determine the compromise solution between the construction and exploitation costs.

Significant changes in the conditions of power systems operation are leading to the necessity to consider significant fluctuations in the electricity prices. As a result there is a need for modification and verification of suitability of traditional deterministic approach. To test the validity of deterministic approach the stochastic method, which is outlined below, has been developed. However, convenience of employ, simplicity of obtaining additional information can pose the task of its development and use as a basic tool for the choice of the parameters of the power system [40, 41].

5.1. The mathematical formulation of the stochastic approach

When formulating the optimization task in question, let us also further preserve the essence of the target function, i.e. let us try to minimize annual expenditure. Besides, let us state that the expenditure c in any time interval can be described by the function φ in the following way:

$$c = \varphi(p_{load}, \beta, t_{amb}, \Pi) \tag{5.1}$$

where p_{load}, β, t_{amb} – the line load, the energy price and the ambient temperature accordingly; Π – includes the set of other parameters influencing annual costs (such as maintenances cost, investments, interest rate).

Analyzing (5.1), we can state that the load, the price and the temperature are random time functions. These functions are not stationary [42]. There are correlation links between them. As a result, it is concluded that c is also the random function in time, since it is determined by appropriate random functions.

In order to describe the multidimensional random process $p_{load}(t),\ \beta(t),\ t_{amb}(t)$, time sampling for this process can be made by setting time moments. The probability distribution functions of the parameters p_{load}, β, t_{amb} are to be assigned for each time moment. These distribution functions can be described by the first, second, … order distribution functions correspondingly [42]:

$$\begin{cases} \Phi_1(P^1_{load}, \beta^1, T^1_{amb}, t_1) \equiv P\{ p_{load}(t_1) < P^1_{load}; \beta(t_1) < \beta^1; t_{amb}(t_1) < T^1_{amb} \}, \\ \Phi_{(2)}(P^1_{load}, \beta^1, T^1_{amb}, t_1;\ P^2_{load}, \beta^2, T^2_{amb}, t_2) \equiv \\ \equiv P\{ (p_{load}(t_1) < P^1_{load}; \beta(t_1) < \beta^1; t_{amb}(t_1) < T^1_{amb});\ (p_{load}(t_2) < P^2_{load}; \beta(t_2) < \beta^2;, \\ t_{amb}(t_2) < T^2_{amb})\}, \\ \ldots \end{cases} \quad (5.2)$$

where P_{load}, β, T_{amb} – the arguments of the distribution functions of the random values p_{load}, β, t_{amb}; the upper indices correspond to the number of the sampling time moment; P – the probability.

Knowing the function (5.1) and the probability distribution functions (5.2), the average value of the random process observation set can be calculated (AVRP) [42]:

$$\begin{aligned} M[C_G] &\equiv M[\varphi(p_{load}, \beta, t_{vamb,} \Pi)] = \\ &= \int_{-\infty}^{\infty} \ldots \int_{-\infty}^{\infty} \varphi(P^1_{load}, \beta^1, T^1_{amb}; P^2_{load}, \beta^2, T^2_{amb}; \ldots) \cdot d\,\Phi_n(P^1_{load}, \beta^1, T^1_{amb}; \ldots; P^n_{load}, \beta^n, T^n_{amb}) \end{aligned} \quad (5.3)$$

Analyzing the equation (5.3) one can easily state that stochastic approach has lead us to formulation of extremely complicated target function, especially for minimization problems solution. Indeed, use of a stochastic approach requires large-scale statistical data and performance of labour-intensive calculations [43]. Existence of this fact has formed the main barrier for stochastic approach implementation. Therefore, due to the rapid development of technologies, especially in the data communication and computing areas, this drawback of stochastic approach becomes insignificant.

5.2. The essence and implementation algorithm of the proposed approach

In the free market conditions, fluctuations of energy prices take place every hour. It means that the amount of discrete time moments and hence the integral dimension can reach a value that is to be estimated at a figure equal to tens of thousands. Under these conditions, it can be stated that the Monte-Carlo method should be used for the calculation algorithm [44].

The essence of the new approach can be expressed as follows: the generation of the random processes is to be conducted by replacing the influencing random processes with other processes that are substantially close to these by their nature.

On Fig. 5.1., an algorithm is proposed, which is based on the probabilistic approach and the Monte-Carlo method (PAMC).

In this part of the Doctoral Thesis, the following two algorithms are used:

- using the linear algebraic expressions that describe changes in the characteristics of the random process in time (for example average value and standard deviation of line power changes in the future).

- by summing up the records of past processes with anticipated changes. In this case, to the load of past years can be attached the planned new energy objects load.

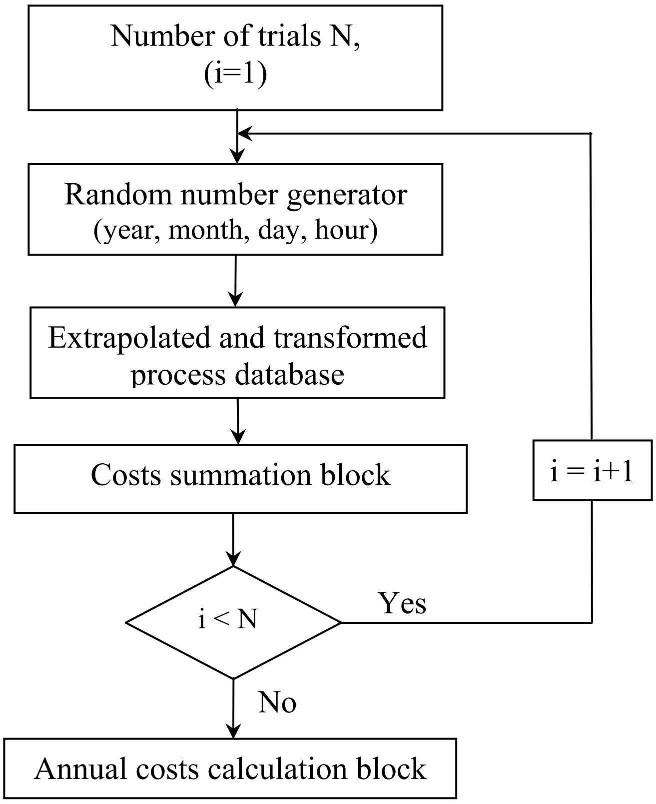


Fig. 5.1. The annual expenditure calculation algorithm (PAMC)

The random process of variations in cost of power losses is egrodic (the term is used to describe a dynamical system which, broadly speaking, has the same behavior averaged over time as averaged over the space of all the system's states). In this case: [39]. In this case:

$$M\{C(t)\} \approx \int_{Ti}^{Ti+8760} \varphi(P_{sl}(t), \beta(t), T_{vid}(t), \Pi) dt \tag{5.4}$$

The PAMC method is very convenient and appropriate for calculating the average costs. The new approach can be implemented by means of software, and it enables a quick and easy solution of the set task. In our case, the MATLAB environment is used.

5.3. An example of using the stochastic approach for choosing the high-voltage line cross-section

Based on the decrease of total annual operating costs, an example of designing a high-voltage overhead line (OHL) is performed. The optimum cross-section calculations are performed for the following two cases: the 110 kV OHL and the 330 kV OHL [45, 46]. The examples show the stochastic method of the calculation of the line annual costs and cross-section on the basis of the following random parameters: the price of electricity β, the ambient temperature T_{amb} and the load of the line P_{load}.

Based on the essence of the new approach (PAMC), a program is developed for choosing the optimum cross-section of the electric line conductors, which consists of two cycles: the internal cycle and the external cycle (Fig. 5.3.).

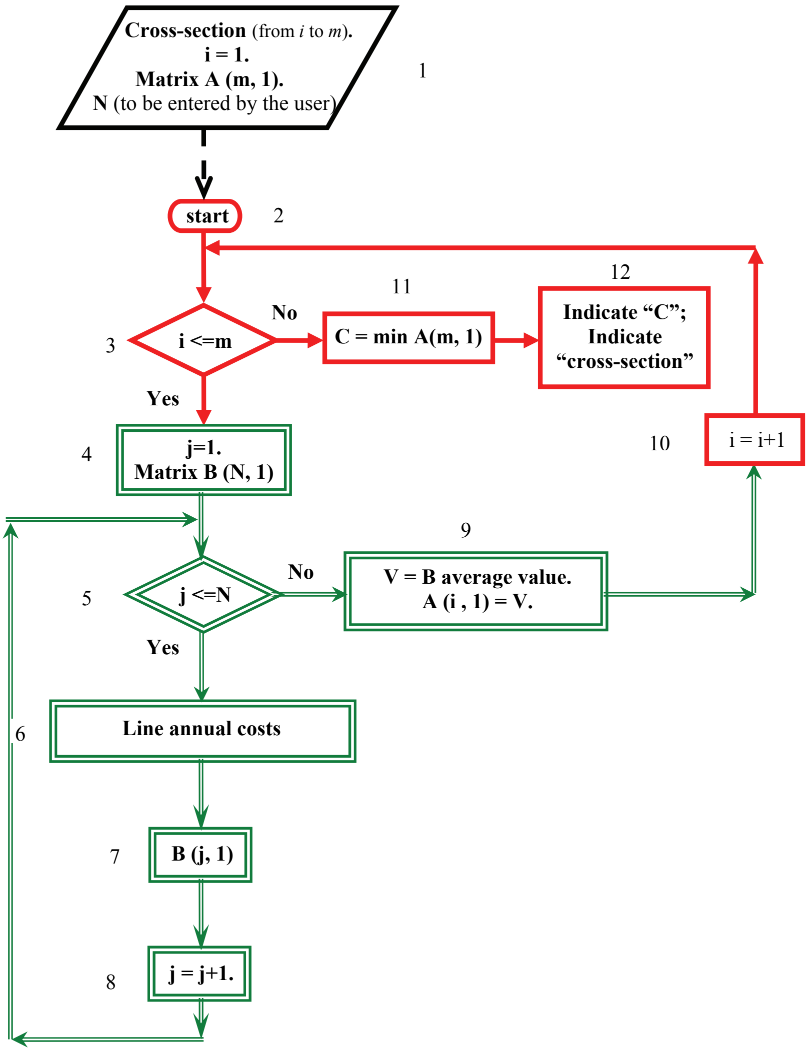


Fig. 5.3. The structure of the optimum cross-section calculation algorithm

The essence of the internal cycle (blocks 4÷9) is the following: the average annual costs are calculated for each cross-section, using the record databases, which are inserted into the program automatically, and the number of trials, which are entered by the user. Within the external cycle (blocks 10÷12), the minimum costs from all the average costs are selected, and hence, corresponding to the minimum costs, the optimum cross-section is determined.

5.3.1. An example of choosing the 110 kV overhead line cross-section

In the first case, the 110 kV OHL is selected, which is to ensure 160 A current.

Using the software "SAPR LEP 2011" [47], which considerably accelerates the process of choosing the optimum transmission network and provides the most advantageous solution, 4 design variants of comparing the steel-aluminium core cross-sections (AS-120/19, AS-150/19, AS-185/29, AS-240/32) in terms of minimization are selected. For each comparison design variant, the annual exploitation and construction costs are calculated, taking into account the power losses costs. According to the essence of the algorithm, the average minimum annual costs at the corresponding cross-section are chosen. The result is shown on Fig. 5.4. and compared with the data of the economic intervals method (Table 5.1.).

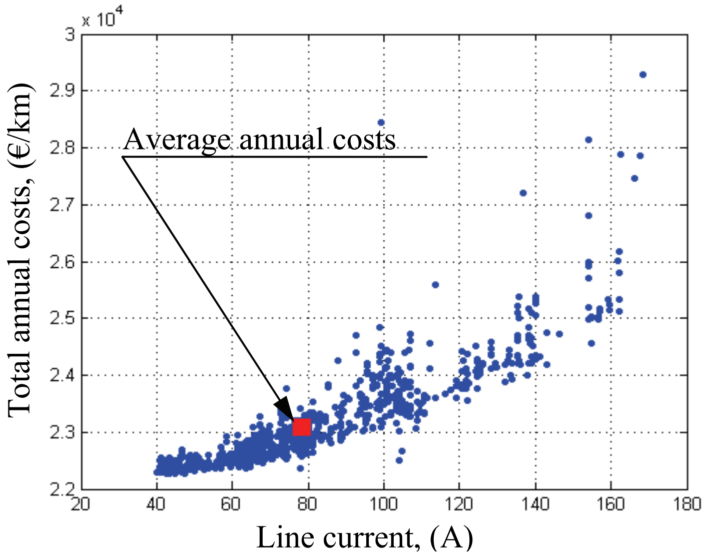


Fig. 5.4. The calculated annual exploitation and construction costs for 1xAS-240 OHL depending on the line current (the PAMC method, 110 kV).

Table 5.1.

A comparison of the results of the methods (110 kV)

	The PAMC method	The economic intervals method
The maximum line current, A	160	160
The annual exploitation and construction costs, €/km	2.3082e+004	2.358+004
The corresponding cross-sections, mm²	240	240

According to the obtained results, it can be concluded that in the first described case, the optimum AS conductor cross-section is 1xAS-240/32. Here, we can observe a small difference in the exploitation and construction cost values: 23082 €/km for the PAMC method, and 23580 €/km (2.11 %) for the economic intervals method.

5.3.2. An example of choosing the 330 kV overhead line cross-section

In the second case, the 330 kV OHL is selected, which is to ensure the 750 A current. Using the above-mentioned software “SAPR LEP 2011”, 4 design variants of comparing the steel-aluminium core cross-sections (2xAS-300/39, AS-400/22, AS-500/27, AS-600/72) in terms of minimization are selected.

According to the proposed PAMC approach, from all the considered design variants, the average minimum annual costs at the corresponding cross-section are chosen. The result is shown on Fig. 5.5. and compared with the data of the economic intervals method (Table 5.2.).

According to the obtained results, it can be concluded that in the second described case, the optimum AS conductor cross-section, using the PAMC method, is 1xAS-600/72. However, using the economic intervals method, there are two possible variants: 1xAS-600/72 or 2xAS-400/22. The differences in the exploitation and construction cost values are a little larger. They amount to 8 % in the first possible variant, and 11 % in the second possible variant.

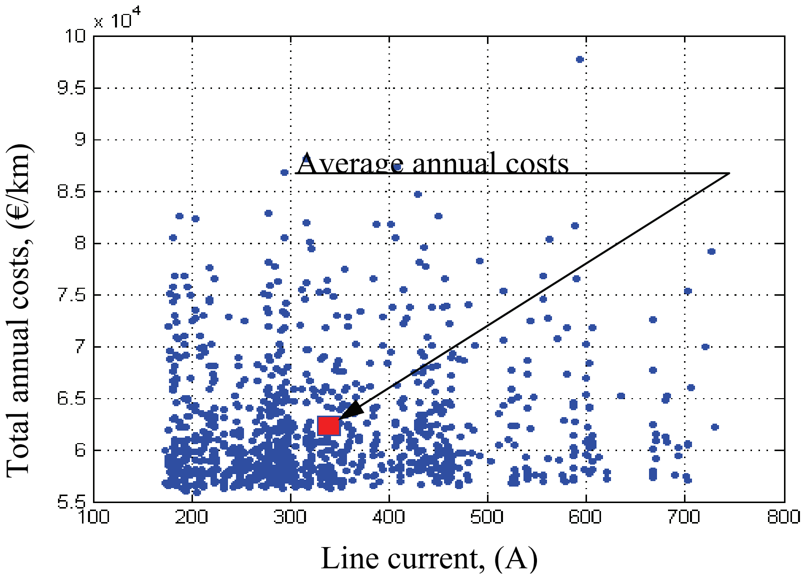


Fig. 5.5. The calculated annual exploitation and construction costs for 1xAS-600 OHL depending on the line current (PAMC method, 330 kV)

Table 5.2.

A comparison of the results of the methods (330 kV)

	The PAMC method	The economic intervals method
The maximum line current, A	750	750
The annual exploitation and construction costs, €/km	6.2323e+004	6.837+004/ 7.029e+004
The corresponding cross-sections, mm^2	1xAS-600	1xAS-600/ 2xAS-400

GENERAL CONCLUSIONS

1. Essential changes take place in the power industry and the power supply of cities of Latvia and the Baltic countries, which requires the development and implementation of a great number of capital-consuming projects.
2. The restructuring of the power systems and the use of market mechanisms essentially change the formulation of the task of substantiation and optimization of energy facility projects, since decisions are to be made in the conditions of wide fluctuations of prices.
3. In order to make a decision substantiating the urban power supply projects, it is necessary to forecast load and price variations in time. The possibility of using the average values of prices and loads under the new (market) conditions becomes doubtful.
4. The traditional, earlier developed methods of solving the development optimization task have become outdated. Changes and verifications regarding the suitability of the traditional and existing approaches as well as searches for new appropriate methods are needed.
5. For solving the power supply optimization task, simplifications and specific approaches are needed. In particular, the geometrical simulation of urban power supply sectors produces a large simplification effect.

6. Determining the load density and constructing cartograms of cities are the effective methods for the facilitation of solving the task.
7. The collection, systematization and correction of the load density data makes it possible to rationally determine the prospective loads of a city or its districts, the capacity of a transformer substation or the location of a new substation. Hence, it is possible to choose the optimal power supply route to the consumers.
8. The choice of cross-sections according to the economical considerations is a topical task in the present-day market economy conditions, when there is a need for substantiated and rational construction of power transmission lines for the prospective development of electrical networks.
9. The current and capacity nomograms gave been developed and the graphical user interface has been created, which can be used in design offices for choosing cross-sections of lines.
10. The comparison of the two methods (the economic intervals method and the PAMC method) has been done, choosing the optimum cross-section. The calculations demonstrate that both considered methods are applicable; however, the PAMC approach is more precise, since it takes into account the real electricity prices as well as the stochastic nature of such parameters as loads and ambient temperature.
11. The PAMC method is proposed and algorithm is to be developed, and after the creation of appropriate software suitable for designers, it is to be put into practice.

LIST OF REFERENCES

1. Козлов В.А. Электроснабжение городов.– М.: Энергоатомиздат, 1988.– 253 с.
2. И.К. Тульчин. Электрические сети и электрооборудование жилых и общественных зданий (1990). 228 стр.
3. Е.А.Конюхова. Электроснабжение объектов.– Москва: Издательство Мастерство, 2002.– 319 с.
4. Svetlana Guseva, Lubov Kozireva, Nataļy Skobeleva. Lielu pilsētu slodzes noteikšana sākuminformācijas nenoteiktības apstākļos. //Scientific Journal of Riga Technical University; Power and Electrical Engineering; 2010. gads.
5. R. Millar, M. Hyvärinen, M. Lehtonen, P. Hämäläinen, "Urban distribution networks-some general planning observations", 20th International Conference on Electricity Distribution, Session 5, Prague, The Czech Republic, 2009.
6. D. Guha, V. Jain, T. Connor, C. Böse, "Greenfield planning approach for the city of Mumbai leads to optimal future network development", Proc. of the 18th International Conference on Electricity Distribution, Turin, 2005.
7. AS Latvenergo, „Nerevidētie saīsinātie konsolidētie finanšu pārskati", 2013.
8. AST Pārvades sistēmas operatora ikgadējais novērtējuma ziņojums (2000–2013).
9. www.sus.lv
10. Latvenergo pārskats, „Elektroapgādes sistēmas modernizācija Rīgā", 21.10.2013.
11. http://www.rdpad.lv/ „Rīgas teritorijas plānojums 2006.–2018. gadam". Paskaidrojuma raksts.– Rīgas dome: 2005.– 97 lpp.
12. AS Latvenergo, "Ilgtspējas un gada pārskats", 2013.
13. Vempers G. Promocijas darbs. Energosistēmu attīstības projektu izvērtēšana brīvā tirgus ekonomikas apstākļos, RTU, 2012.
14. Gerhards J., Mahņitko A. Energosistēmu režīmu optimizācija.– Rīga: RTU, 2005.– 249 lpp.
15. Krišāns Z., Oļeiņikova I., Elektroenerģētisko uzņēmumu vadības pamati. Rīga; Rīgas Tehniskā Universitāte 2007;

16. Skobeļeva N. Promocijas darbs. Pilsētas elektrotīkla optimālo parametru izvēle attīstības projektu sākumstadijās, RTU, 2012.
17. S.Guseva, O.Borscevskis, N.Skobeleva, L.Petrichenko. Load determination and selection of transformer substations' optimal power for tasks of urban networks' development//Enerģētika un Elektrotehnika, sēr. 4., 27. sēj., 2010, 31.–36. lpp.
18. N.Skobeleva, O.Borscevskis, S.Guseva, L.Petrichenko, "An integrated approach to the formation of service areas for urban substations of different voltage", Journal of Energy and Power Engineering (ISSN1934-8975), David Publishing Company, Inc. USA, Vol. 6, No. 8, August 2012, pp. 1358–1362.
19. S.Guseva, O.Borscevskis, N.Skobeleva, L.Petrichenko, "Urban Power supply system's development in conditions of uncertain information", Proc. of the Tenth IASTED European Conference "Power and Energy Systems", Crete, Greece, 2011, pp. 27–31.
20. Справочник по проектированию электрических сетей. /Под ред. Д.Л.Файбисовича, издание 2-е,– Москва: Издательство НЦ ЭНАС, 2006 г.– 102 с.
21. РМ-2696-01. Временная инструкция по расчету электрических нагрузок жилых зданий. Введена в действие с 31.07.2001.– Москва: МНИИТЭП.
22. РД 34.20.185-94. Нормативы для определения расчётных электрических нагрузок зданий (квартир), котеджей, микрорайонов (кварталов) застройки и элементов городской распределительной сети. Введена в действие с 29.06.1999.- Москва: МНТОЭ.
23. Дуброва Т.А. Статистические методы прогнозирования: учеб. пособие для вузов. — Москва: ЮНИТИ-ДАНА, 2003.;
24. Бэнн Д.В., Фармер Е.Д. Сравнительные модели прогнозирования электрической нагрузки: Пер. с англ.– М.: Энергоатомиздат, 1987.– 200 с.
25. Шумилова Г.П., Готман Н.Э., Старцева Т.Б. Модели прогнозирования нагрузок на основе аппарата искусственных нейронных сетей // Методические вопросы исследования надежности больших систем энергетики. Вып. 51. Сыктывкар: Изд-во Коми НЦ УрО РАН, 2000.
26. http://www.mathworks.se/help/econ/arima.forecast.html
27. Kozireva Ļ. Maģistra darbs. Rīgas pilsētas elektroapgādes sistēmas attīstība, RTU, 2010.
28. S.Guseva, L. Petrichenko, N.Skobeleva. Load Density Distribution and Assessment for Urban Power Supply System // The 4th International Conference on Power Engineering, Energy and Electrical Drivers, 13–17 May 2013, Istanbul, Turkey
29. Блок В.М., Астахов Ю.Н., Лариньш К.В., Гусева С.А., Бейерс И.В. Метод выбора сечений кабелей по универсальным номограммам. Электричество, 1976, Nr. 8, 24–27 стр
30. В.М.Блок. Электрические сети и системы. Москва « Высшая школа», 1986г.
31. 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, Nr.3.
32. A.Vanags, Z.Krišāns. Elektriskie tīkli un sistēmas, II daļa, 2005. g., RTU izdevniecība.
33. Г.Е.Поспелов, В.Т.Федин. Электрические системы и сети проектирования, 2-изд., испр., допол., Минск, «Высшая школа», 1988г.
34. Энергетические системы в примерах и иллюстрациях. Под редакцией В.А.Веников. Москва: Энергоатомиздат, 1983, 499 стр.

35. Г.Е.Поспелов, В.Ф.Свидерский. Экономические интервалы некоторых параметров электрической сети с учётом динамики роста нагрузки. Электричество, 1973. Nr.5, 12–16 стр
36. Berjozkina S., Sauhats A., Bargels V., Vanzovichs E. The Technical and Economic Efficiency of Using Conductors with Composite Core in the Transmission Grid// Proceedings of the 9th International Conference on the European Energy Market EEM12.– Florence, Italy: IEEE, 2012.– p. 7.
37. Guseva S., Petrichenko L. Choice of the optimum cross-sections for 20-110-330 kV overhead lines under market conditions // Latvian Journal of Physics and Technical Sciences, No 6(1) (Vol. 49), Riga, Latvia, 2012, p.13–22.
38. S. Guseva, L.Petrichenko. Approach of Optimum Cross-Section Choice for Cable Lines in Market Prices Conditions. Power Engineering 2012, High Tatras – Tatranske Matliare, May 15–17, 2012, Slovakia, p. 87–88.
39. РД 16.405-87 «Расчет масс материалов кабельных изделий».
40. V. Neimane, On development planning of electricity distribution networks. Doctoral dissertation, Stocholm: 2001.
41. F. Kiessling, P. Nefzger, J.F. Nolasco, U. Kaintzyk, “Overhead Power Lines Planning, Design, Construction”, Springer-Verlag Berlin Heidelberg New York: 2003, 759 p.
42. Г. Корн, Т. Корн. Справочник по математике для научных работников и инженеров. Изд. 4, М., 1978, 832 стр.
43. http://www.nordpoolspot.com/
44. И.М.Соболь «Метод Монте-Карло», М., 1985.
45. L.Petrichenko, A.Sauhats, S.Guseva, S.Berjozkina, V.Neimane. The stochastic approach for determination of transmission line wire cross section// The 2014 International Conference on Power Systems, Energy, Environment, Interlaken, Switzerland, February 22–24, 2014
46. S. Berjozkina, A. Sauhats, V. Bargels, E. Vanzovichs, “The Technical and Economic Efficiency of Using Conductors with Composite Core in the Transmission Grid”, in Proc. of the 9th International Conference on the European Energy Market (EEM12), pp. 1–7.
47. The special program “SAPR LEP 2011” description. Modern design System. [Online]. Available: http://www.bsapr.ru/prod/progs/element.php?ID=250 [krievu valodā].