RIGA TECHNICAL UNIVERSITY

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SELECTION OF URBAN NETWORK'S OPTIMUM PARAMETERS AT EARLY STAGES OF DEVELOPMENT DESIGNS

Summary of Doctoral Thesis

Riga 2012

RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
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Doctoral Program in Power and Electrical Engineering

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DOCTORAL THESIS IS PROPOSED FOR ACHIEVING DR. SC. ING. DEGREE AT RIGA TECHNICAL UNIVERSITY

Doctoral Thesis is proposed for achieving Dr.Sc.Ing. degree and will be publicly presented at 14:30 on the 6th of June 2012, at Faculty of Power and Electrical Engineering of Riga Technical University, 1 Kronvalda boulevard, in the assembly hall

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CONFIRMATION

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 has not been submitted to any other University for achieving scientific degree.

Natalja Skobeleva ……………………………………...
(signature)
Date: ………………………

The Doctoral Thesis is written in Latvian language, it contains an introduction, 5 chapters, conclusions, bibliography, and one appendix. The total volume of thesis is 154 pages, 83 figures, 37 tables and 1 appendix. The List of bibliography includes 82 sources of literature.

Contents

TOPICALITY OF THE DOCTORAL THESIS

Electric networks of large cities are a part of state power system or regional power supply system that is continuously developing along with the power supply system as a whole. Elements of a real system make a single whole, therefore, to build a rational system, the relationship between individual parts of the system, which provides the largest possible feasibility of technical and economic indicators, should be elaborated. The great importance in creation of rational, logical and consecutive network belongs to elaboration of main principles for execution of the network scheme and the concept of its development.

In the beginning of XXI century, a significant growth of electrical load and electrical energy consumption in residential and administrative districts and industrial areas of Latvian cities was observed. That was happening thanks to the developing technology in public utility and industrial production sector and growing standard of living. As requested amount of electric power increases, load density in different city areas changes thanks to construction of residential, commercial, cultural, business, administrative and other facilities, and building of new housing estates. This creates a need for changes in the network: building new lines and transformer substations (TA) and reconstruction of the existing ones. Today, construction of new substations and connection them to the network is a complex process, as in the cities there already exist electric networks, which should be preserved as far as possible. The concentrated development of the central districts of the city and a considerable quantity of engineering communications create complexities and complicates location of new substations and a lining of new cable lines.

To create more reliable and efficient power supply system general network planning and construction principles should be formulated, which would allow for future expansion of the network with no need for crucial changes. Urban power supply system development should be spent in a complex and in coordination for networks 330-110 кV and 20-10 kV. It has to be systematic, technically and economically substantiated. It is important to objectively assess the prospective loads, to select optimum or rational parameters of networks at early stages of designs, to provide introduction of new capacities as needed and necessary reserve of capacity for new connections, to develop the principles for location of prospective substations, as well as sequence of construction of new elements of the system.

The strategy of development of urban power supply system shall include medium- and long-term planning. However detailed study of projects often is absent and the initial information in the necessary amount is not available to ensure such planning. The aggregate load of the city and urban districts is heavily influenced by consumers' total requested load. Its size and connection terms to a network have casual and uncertain character.

This means that the development tasks are solved and decisions on the development direction and selection of optimum parameters are made in conditions of incomplete and uncertain initial information. The accepted development forecasts and options have to be adjusted periodically as new data is received.

Selection of the development direction is complicated due to economic situation in the country. A few years ago the situation the city of Riga had developed to critical. There was approximately 300 MVA prospective load demand, which couldn't be connected to the existing grid. The situation changed in 2007 as the economic crisis began. Load and power consumption decreased in the city and the power supply system, development of many designs and many construction sites were suspended. Although load growth has stopped in Riga now, the network has to be prepared for load increase, and connection of new consumers in the future.

Taking into account the above-mentioned, elaboration of a rational and reliable urban power supply system concept and its development was chosen as the Thesis research direction.

GOAL AND OBJECTIVES OF THE THESIS

The goal of this Thesis is developing common principles for formation of urban power system and the methodology for selection of optimum parameters and development of the city networks at early design stages in the conditions of incomplete and uncertain data.

To achieve the goals the following objectives have been identified:

- analyse the principles of formation of the power supply grids in the biggest European cities to select the principles of formation of the power supply system in Riga;
- make forecasts for power loads in Riga and evaluate the existing and expected loads of 110 kV power substations in 2020;
- elaborate methodology for rational development scheme: evaluate installed transformer capacities, service areas and radii of prospective substations, formulate principles for location of transformer substation in the city areas;
- develop options for prospective Riga power supply system scheme for the year 2020 and carry out feasibility study of the optional scheme.

SCIENTIFIC NOVELTY

Scientific novelty of this Thesis is achieved thanks to the following aspects:

- Systemic approach based on system integrity, unity and developability has been applied to form Riga City power supply system;

- Corrections of Riga City load until 2020 forecasts and definition of prospective 110/10 kV transformer substations' loads taking into account the unstable situation in national economy and energy sector were made.
- Mathematical and geometrical modelling of the city power grid based on uniform principles to ensure equal approach to formation of each hierarchical level of the grid was carried out.
- Optimum capacities of prospective 110/10 kV transformer substations by criterion of a minimum of total capital investments on creation of 110-10 kV network are defined and on the basis of this size optimum service areas and radii are received.
- Placement of transformer substations at the Riga City Development Masterplan was performed using the geometric templates of transformer substations' service areas and by means of application program „TASAD" in Microsoft Excel environment and graphic software AutoCAD.
- Options for perspective Riga 110 kV power supply scheme for 2020 were developed, one of which was accepted at JSC „Latvenergo" Expert Council on 2 February 2009 as a basis for the network to be formed in the future.
- The large city development problems were solved and decisions were made in the circumstances of incomplete and uncertain data for 10-15 years prospective.

METHODS AND MEANS OF RESEARCH AND DEVELOPMENT

For acquiring the results of this Thesis the following methods of research and development were applied:

- mathematical and geometrical modelling of the research object;
- optimization of the objective function to ensure selection of electrical network parameters at early stages of a development design by means of comparison of network construction options and definition of the function minimum;
- for problem solution calculation and graphic software was used: calculation application in Microsoft Excel environment, MathCAD, graphic software AutoCAD, CorelDraw Graphics Suite, and Photoshop.

PRACTICAL APPLICABILITY OF THE RESULTS

The methodology developed in this Thesis makes the power supply network development concept and principles applicable for rational planning of power supply systems of large cities and basically can be used for solution of similar development problems for small cities.

The methodology has been applied in practice for development of Riga City perspective power supply network until the year 2020 within the framework of two Riga Technical University and JSC „Latvenergo" contracts: No. L7280

(No.010000/07-200 dated 16.05.2007) and No. L7310 (No.010000/09-16 dated 15.01.2008).

APROBATION OF THE THESIS

The results of the research have been reported and discussed during 10 international conferences as follows:

1. The tenth IASTED European Conference "Power and Energy Systems", 22-24 June, 2011, Crete, Greece.
2. 6-th International Conference on Electrical and Control Technologies, ECT-2011, 5-6 May, 2011, Kaunas, Lithuania.
3. The 51st International Scientific Conference „Power and Electrical Engineering", section „Power Engineering", 14-16 October, 2010, RTU, Riga, Latvia.
4. The International Energy Forum 2010, 23-26 June, 2010, Varna, Bulgaria.
5. XI International Scientific Conference „Problems of Present-day Electrotechnics, PPE-2010", 1– 3 June, 2010, Kyiv, Ukraine.
6. 5-th International Conference on Electrical and Control Technologies, ECT-2010, 6-7 May, 2010, Kaunas, Lithuania.
7. 50-th International Scientific Conference „Power and Electrical Engineering", section „Power Engineering", 14-16 October, 2009, RTU, Riga, Latvia.
8. 49-th International Scientific Conference „Power and Electrical Engineering", section „Power Engineering", 13-15 October, 2008, RTU, Riga, Latvia.
9. VI Международный Форум „Электротехника-2008", Петербургский энергетический институт повышения квалификации „ПЭИПК", 15-19 сентября, 2008, Санкт-Петербург, Россия.
10. XI International Scientific Conference „Problems of Present-day Electrotechnics, PPE-2008", 5-9 June, 2008, Kyiv, Ukraine.

18 articles have been issued in international publications:

1. **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, David Publishing Company, Inc. USA, 2011 (passed for press in USA).
2. Svetlana Guseva, **Nataly Skobeleva**, Oleg Borscevskis, Lubov Petrichenko. Urban Power supply system's development in conditions of certain information //Proceeding of the Tenth IASTED European Conference "Power and Energy Systems", Crete, Greece, 2011, CD, p. 27-31.
3. S.Guseva, O.Borscevskis, **N.Skobeleva**, L.Petrichenko. Perspective loads of transformer substations at development of urban power supply systems //Proceeding of the XV International Scientific Conference "Present-day problems of power engineering APE'11", 8-10 June, 2011, Jurata, Poland, 2011, p. 51-59.
4. Nikolajs Breners, Svetlana Guseva, **Nataly Skobeleva**, Oleg Borscevskis. Directions to increase reliability of maintained transformer equipment`s functioning // Proceeding of the 6th International Conference on Electrical and Control Technologies ECT 2011, 5-6 May, 2011, Kaunas, Lithuania, p. 175-178.

5. **Nataly Skobeleva**, Oleg Borscevskis, Svetlana Guseva, Lubov Petrichenko. An integrated approach to the formation of service areas for urban substations of different voltage //The 6th International Conference on Electrical and Control Technologies ECT-2011, May 5-6, 2011, Kaunas, Lithuania, p. 202-205.
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10. S.Guseva, **N.Skobeļeva**, O.Borscevskis, N.Breners. Geometrical modelling of service areas and distribution of urban transformer substations in the city territory // Proceedings of the XI International Scientific Conference „Problems of Present-day Electrotechnics, PPE-2010", June 1-3, 2010, Kyiv, Ukraine, CD, 4 p.
11. S.Guseva, **N.Skobeļeva**, N. Breners, O.Borscevskis. Determination of service areas of urban transformer substations and distribution using geometrical templates // Latvian Journal of Physics and Technical Sciences, No 6 (Vol. 47), Riga, Latvia, 2009, p. 16-26.
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STRUCTURE AND ORGANIZATION OF THE THESIS

This Doctoral Thesis contains an Introduction, 5 chapters, a Conclusion, a Reference index with 82 titles. The Thesis includes 83 figures and 37 tables. The Thesis consists of 154 pages in total.

Chapter One contains analysis of Riga transformer substations load dynamics, description of the condition of 330 and 110 kV power supply networks, description of principles of the "ideal" urban power supply system and their application and realization for power supply networks in Riga and some foreign cities.

Chapter Two includes summarized information about power consumption and load forecasting methods, description of load evaluation methods using generalized indicators and electric load in Riga City in 2020 forecasts according to different scenarios. Presence of load density hierarchy according to hierarchy of voltage is theoretically proved.

Chapter Three is dedicated to mathematical and geometrical modelling of the transformer substations' service areas and radii, defining graphical dependencies of these values and load density value. The Chapter also includes analysis of changes of service areas through the development and operation of the network.

Chapter Four contains definition of prospective load of 110/10-20 kV transformers and their distribution over the territory of the city (shown on the Riga City Masterplan) up to the year 2020. All the necessary developments were made using calculation application program „TASAD” in the Microsoft Excel environment and graphic software AutoCAD.

Chapter Five is dedicated to development of a mathematical model to evaluate optimum installed capacity of 110/10 kV transformers in urban districts and analysis of prospective options for the power supply system in Riga for the period until 2020; technical and economic estimation has been carried out for each of the options.

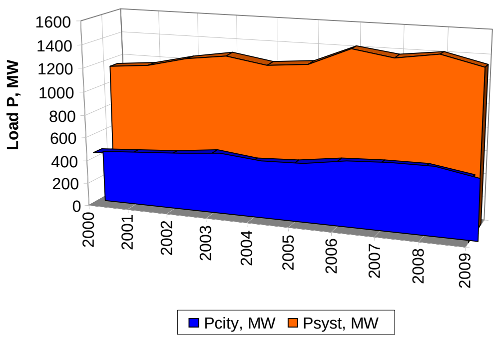
1. PRINCIPLES OF FORMATION OF LARGE CITY POWER SUPPLY SCHEME

1.1. Description of Riga power supply system

Consumption of electrical energy by the largest Latvian cities accounts for two thirds of the total country consumption. Cities are important consumers of electrical energy, as the majority of the population lives in them, as well as many industries are located in the large cities. There is systematic increase in electricity consumption by the population for domestic purposes as saturation of household appliances grows. Cities are public utility objects, the electrical load and power consumption of which is comparable to similar amount for large industrial plants. The largest electricity consumer of the Latvian power supply system is its capital, Riga City.

To create a safe and cost effective urban city power supply system (UPSS), one should identify the general principles of construction of the network, which would make it possible to form a rational system of electricity supply, capable of expansions without crucial changes in the future, decide on rational distribution of prospective substations and power supply sources, as well as to establish a sequence of construction of new system elements. In order to provide uninterrupted power supply to the consumers a flexible, reliable, economically well-founded electric scheme is required. Some problems were solved using Riga power supply system as an example, analyzing load dynamics of Riga transformer substations (TS) in recent years and reviewing the development of Riga networks for the year 2020 perspective.

During the period of favourable economic development from 2000 to 2007 there was steady annual increase in electrical load as the dynamics in Fig. 1.1 shows. This growth stopped due to the global economic crisis, and in 2008 the load in Riga began to diminish.



t,year	Psyst,MW	Pcity, MW
2000	1137	442,2
2001	1165	468,8
2002	1248	490,5
2003	1297	529,6
2004	1240,3	492,8
2005	1270,8	507,6
2006	1420,6	561,3
2007	1373	578,4
2008	1419	580,8
2009	1340	522,1
2010	1342	485

Fig. 1.1. Riga City maximum load dynamics

The situation with the load in the city is hardly predictable for the coming years and further perspective, nonetheless the development process should continue. Although currently growth of loads stopped in Riga, the network has to be prepared to the further growth of loads and connection of new consumers to an electric network.

Currently, the city of Riga basically receives electrical energy from a united Latvian 330/110 kV power grid, which covers the city in the both banks of the Daugava river and connects the power production centers and transformer substations [26-28]. The key energy suppliers for Riga are: the Riga Hydropower Plant (HPP) with a capacity of 402 MW and Riga Combined Heat Power Plant (CHPP) -2 (RTEC-2) with a capacity of 662 MW, which are located outside the territory of Riga City. Within the city, Riga CHPP-1 (RTEC-1) with a capacity of 144 MW and low capacity (48 MW) cogeneration block Imanta provide electricity to the consumers. There are fifteen 330 kV substations in Latvia of which three are situated in Riga.

All the power suppliers are connected to the 330 kV lines and form a 330 kV half ring (Fig.1.2). Riga city power supply providing is dependent on the 330 kV network. To increase the reliability of power supply it is necessary to create a 330 kV ring in the territory of Riga, as the existing city 330 kV grids is operated radially. The decision on construction of a 330 kV cable line between substations Imanta – RTEC-1 has been accepted within the framework of the project "Kurzeme Ring". By connecting these substations the Riga 330 kV circle will be fully closed. As a result, the 110 kV network will be less loaded and power transmission losses reduced, power supply reliability will increase.

110 kV transmission network of the city is formed as a ring. The existing 110 kV network operates in closed loop regime. The ring is powered from 330/110 kV primary substations Bisuciems, Imanta, RTEC-1 and substation RTEC-2 located outside Riga. 330/110 kV primary substations have links to the 110 kV transformer substations. 27 substations of 110 kV high voltage out of all the 119 Latvian substations are located in Riga. The age of transformers at substations and autotransformers varies rather significantly. Analysis of 110 kV transformers' age is given in Figure 1.3. According to the diagram the lifetime of 55 per cent of the transformers does not exceed 25-30 years, which is permissible. In recent years, reconstruction and upgrade of the substations' equipment of the Riga circle was started, also it will be continued in future [11, 13, 15, 19-23].

110 kV network has got a great ring covering the city built-up areas, and small loops, which provide 110 kV substations with two-way or multi-way feeding inside the greater ring. There is one diametric link connecting primary

substations Bisuciems and RTEC-1. Substations Hansa and Janciems are bound through diagonal star connections to the primary substations Bisuciems, RTEC-1 and RTEC-2.
The analysis of the Riga 110 kV networks scheme shows that its principles of execution are similar to the "ideal" scheme [26, 27].

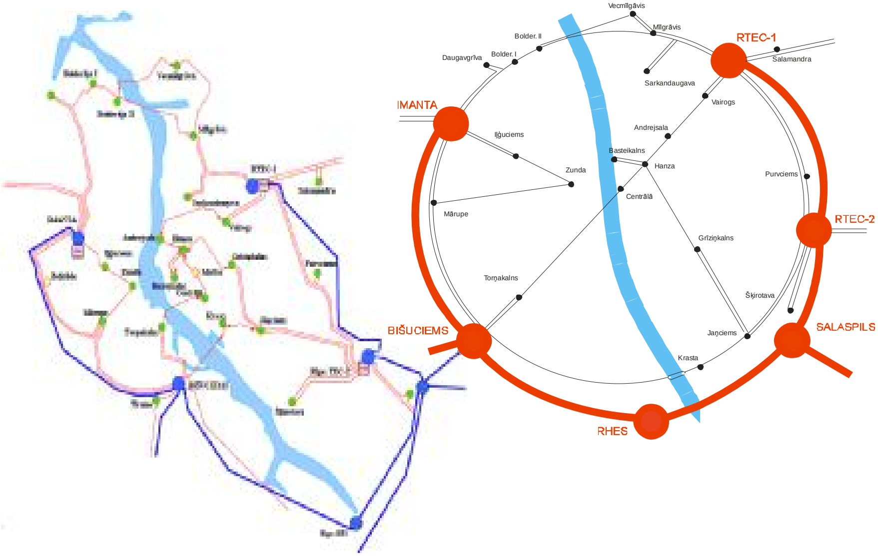


Fig. 1.2. Existing Riga City networks and idealized scheme for 2008

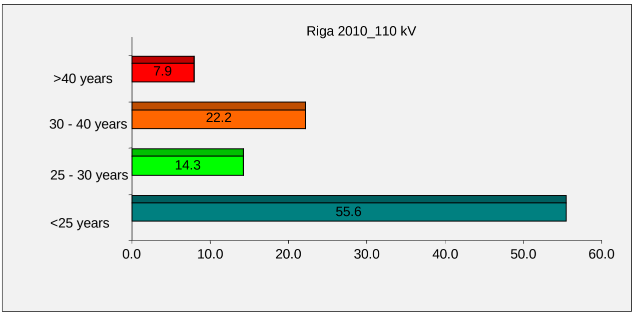


Fig. 1.3. 110 kV transformers division by age in 2010, %

1.2. "Ideal" power supply scheme

The classical "ideal" urban power supply scheme proposed in Germany in the fifties of last century is based on 110/10 kV voltage system. 110 kV network was formed as a ring covering the city and performing busbar system functions to receive power from power generation centers: local power stations and/or 220-330 kV (and more) transformer substations (see Figure 1.4). The ring ensures parallel operation of the supply centers. The central part of the city is fed by a considerably large 110/10 kV substation. It is powered from a diametric link through the city. The 110/10 kV substation located along the ring ensure power feed to 10 kV distribution networks. For a more effective distribution of capacity through the ring and its correct operation the power supply centre and 110 kV substations' connection to 110 kV ring should be replaced. The "ideal" 110 kV network throughput capacity could be increased by "cutting" of the ring and connection of 110 kV lines to new power supply centers, as well as increasing the number of new 110 kV lines (See Figure 1.5), i.e., repeating of the ring. Connection of new power supply centers to 110 kV ring network makes it possible to enhance its capacity without radical reconstruction of the network. The “ideal” scheme of power supply meets the basic requirements of the rational scheme for large city [26, 27].

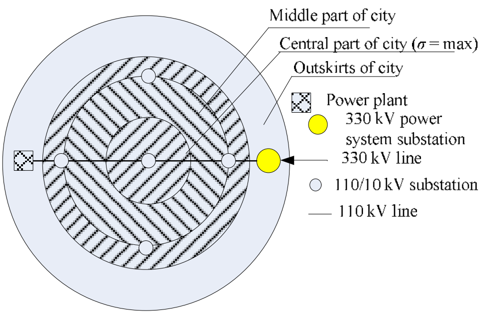


Fig. 1.4. Model of ”ideal” scheme of city power supply

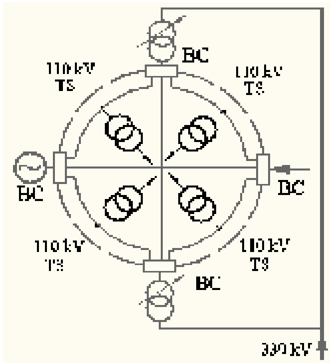


Fig. 1.5. Connection of power supply centers and 110/10 kV substations to the 110 kV ring

The existing Riga power supply scheme, if compared with the "ideal", has got some implementation peculiarities that are related to the geographical location of the city (a large river, which divides the city into two parts), the historical development of the city and lack of single concept of the power supply system long-term development.

1.3. Analysis of urban power supply system's abroad

The principles of an "ideal" circuit have been implemented in many cities abroad, taking into account their geographical location, construction principles, network design and other characteristics. Further the power network implementation in West Berlin, Stockholm, Helsinki, Tallinn, Vilnius, Moscow, and St. Petersburg is reviewed [26, 27].

The highest load density is usually in the central part of large city, because public institutions, banks, offices and bureaus, cultural and public institutions and other buildings, large-scale energy consumers, are located there. In addition, in the central part finding a location for new substations and electrical connections is complicated. City streets are usually overloaded by engineering communications that complicates building of new cable lines. It is not possible sometimes to provide power for large concentrated loads. In order to increase the reliability of substations a multi-way power supply should be provided. This results in node and star connections that complexity the circuits.

Having reviewed a number of the European cities' power networks one can conclude that most urban 110 kV power supply networks have been formed as a ring with a diagonal connection between substations, which are the features of the "ideal" scheme of power supply. Connecting of 110 kV substations to each other by two lines (a double-circuit circle) in some cities like Helsinki, Tallinn and Vilnius is related to the need to enhance reliability of the power supply system, as there is no ring of voltage higher than 110 kV around these cities. Power supply networks in the cities are designed with both overhead and the cable lines, however in the centers of the cities; overhead lines are being replaced with cable lines during reconstruction of the mains.

Practical implementation of the "ideal" scheme in large cities is not so easy, and, depending on local conditions, the power supply system of each particular city has its own characteristics, even if the scheme in general is rather similar with the classic "ideal" scheme.

2. FORECASTING AND DETERMINATION OF CITY ELECTRICAL LOAD IN THE CONDITIONS OF UNCERTAIN INFORMATION

This Thesis was developed in the period from 2007 until 2011 marked by rapid changes in national and global economic and financial sector. The consistently growing Gross Domestic Product (GDP), increasing electricity demand in Latvia and Riga since 2000, stopped in 2007 and subsequently diminished due to the economic crisis. In unstable economy, it is difficult to forecast electricity demand and network elements' load for the future, as previously developed predictions do not reflect reality, relationships and indicator time trends have been interrupted. To prove this, a number of electricity and power forecasts acquired from JSC „Latvenergo” and Directive Documents were reviewed and compared [10]. The conclusion is that it is not reasonable to use sophisticated and accurate methods of forecasting in unstable economies as indicators' behaviour is not stable and is difficult to predict. Given the aspect of uncertainty affecting prediction, the power consumption and load forecasts should be regarded not as a definite value, but as a value range, which probably include the expected indicator. During this period, it is advisable to periodically adjust the forecasts as some additional data is received. The indicators' curves and trends may be specified after the economic situation will have stabilized.

During development of this Doctoral Thesis, the optimistic forecast taking into account favourable development conditions made by JSC "Latvenergo" for 2006 was adjusted, then, upon receiving additional information, adjustments were made to the year 2007, 2009 and 2010 [2, 3, 10].

To adjust forecasts data statistics prepared by JSC "Latvenergo" Research and Development Department about the aggregate load of the existing substations in Riga in 2000 – 2007 and additional information from 2008 to 2009 was used. A close interrelation between loads of a power system and Riga City of Riga with 2000 to 2009 (correlation factor: $R_{X,Y}$ = 0.9634), has been taken into account also. The modified forecasts for various scenarios of development are given in Figure 2.1 and 2.2.

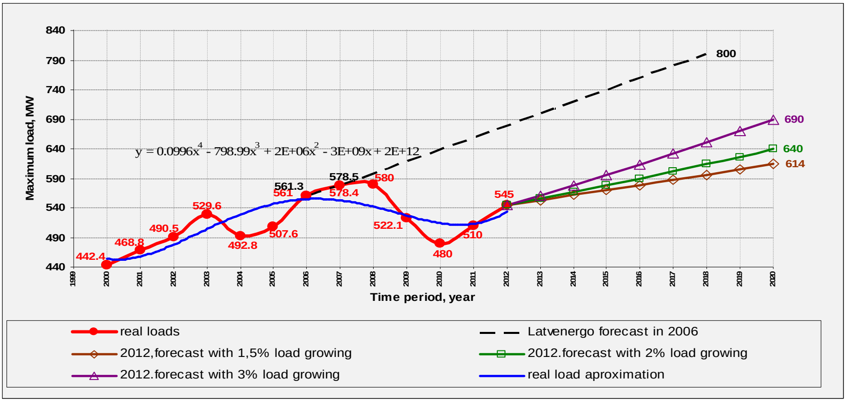


Fig. 2.1. Riga electrical load forecast for 2010 – 2020 indicating recession in 2009 – 2012 (correction made in 2009)

To determine the aggregate load of the city a factor of simultaneity of the 110 kV transformer substations was applied. Total aggregate electric load of the city for any year can be acquired as follows [14]:

$$S_{City} = k_{o,TS} \cdot \sum_{i=1}^{n_{TS}} S_{TS,i} = k_{o,TS} \cdot \sum_{i=1}^{n_{TS}} P_{TS,i} / \cos j \quad , \qquad (2.1)$$

where S_{City} is total aggregate electric load of the city in the given year, MVA; $S_{TS,i}$ is the full load of the i–th 110 kV substation in the given year, MVA; $P_{TS,i}$ is active load of the i–th 110 kV substation in the given year, MW; $k_{0,TS}$ is a factor of simultaneity of maximum load of the transformer substations depending on the number of 110 kV TS, accepted equal 0,9; n_{TS} is the number of 110 kV transformer substations located in the city; cos φ is network power factor, accepted equal 0,9.

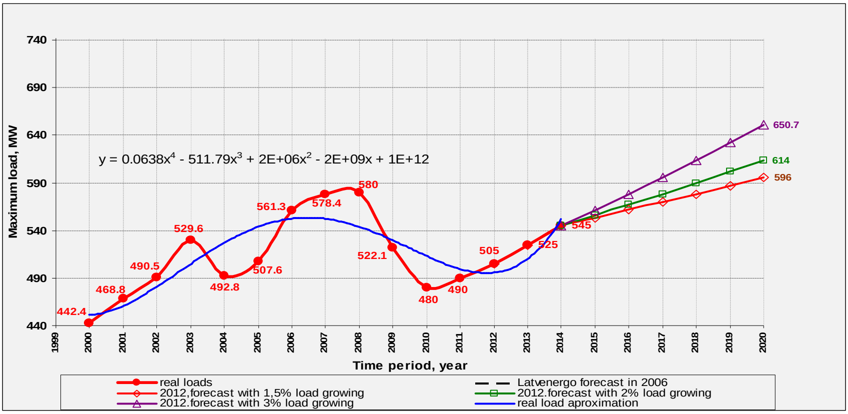


Fig. 2.2. Riga electrical load forecast for 2010 – 2020 indicating recession in 2009 – 2014 (correction made in 2009)

Taking into account different forecasts the Riga electric load in 2020 could be expressed in the values listed in Table 2.1.

Table 2.1

Different forecasts of perspective Riga City electric load for the year 2020:

A. Stable economy (according to 2006 forecast)

Load increase, %	$\sum P_{TS,i}$, **MW**	S_{City}, **MVA**
3%	848	848
1,9%	738	738

B. Unfavourable economy development (according to 2008 forecast, in case of recession lasting until 2012 / 2010 forecast, in case of recession lasting until 2014)

Load increase, %	$\sum P_{TS,i}$, **MW**	S_{City}, **MVA**
3%	690 / 650	690 / 650
1,9%	634 / 610	634 / 610
1,3%	604 / 589	604 / 589

In addition to forecasting methods, techniques employing generalized indicators proposed in the literature were analyzed and adjusted to Latvian conditions [10].

1. Electrical load determination method employing specific rated load in public utility sector and the population

The approached rated load of the city or its district can be calculated using the expression:

$$P_{est} = k_{LInc} \cdot p_L \cdot N_{pop} \quad , \tag{2.2}$$

where p_L is specific rated active load (per person) in public utility sector, kW/pers; N_{pop} is the population of the city, its district or a residential area, pers.; k_{LInc} is load increase factor, that takes into account loads of minor industrial and other consumers that receive power from city distribution networks.

2. Electrical load determination method employing specific power consumption in public utility sector and the population

The approached rated load of the city or its district can be calculated using the expression:

$$P_{est} = k_{ConsInc} \frac{p_{cons} \cdot N_{pop}}{T_{max}} \quad , \tag{2.3}$$

where p_{cons} is specific power consumption (per person) in the public utility sector, kWh/pers; $k_{ConsInc}$ is power consumption increase factor, that takes into account loads of minor industrial and other consumers that receive power from city distribution networks; T_{max} is the utilization time of maximum load per year, h; N_{pop} is the population of the city, its district or a residential area, pers.

3. Electrical load determination method employing specific rated load in public utility sector and living floorage in built-up areas

The approached rated load of the city or its district can be calculated using the expression:

$$P_{est} = k_{LInc} \cdot k_{light} \cdot (p_{res} + p_{adm}) \cdot F_{city} \, , \tag{2.4}$$

where p_{res} is specific rated active load of residential houses, kW/m^2 ; p_{adm} is specific rated active load of administrative building in the district, kW/m^2 ; F_{city} is housing stock of the city or its district, m^2; k_{light} is the factor that takes into account the load of the city electric lighting.

4. Electrical load determination method employing average load density and size of built-up area

This method is based on the average load densities in existing or prospective districts of the city with various-storey building sites. Method has got certain advantages because most of the necessary information can be obtained from the energy companies and department of city development.

The total aggregate electric load of the city can be calculated as follows:

$$S_{city} = \sigma_{av} \cdot \Pi_{city} = \sigma_{av} \cdot \sum_{i=1}^{n_{TS}} \Pi_{TS,i} \ , \tag{2.5}$$

where σ_{av} is 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 service area of the *i*-th substation, km^2; n_{TS} is the number of transformer substations.

Based on the condition of equality of (2.1) and (2.5):

$$\sigma_{av} = \frac{k_{o,TS} \sum_{i=1}^{n_{TS}} S_{TS,i}}{\sum_{i=1}^{n_{TS}} \Pi_{TS,i}} = \frac{k_{o,TS} \sum_{i=1}^{n_{TS}} n_i \beta_i S_{r,i}}{\sum_{i=1}^{n_{TS}} \Pi_{TS,i}} \ , \tag{2.6}$$

where n_i is the number of transformers in the *i* –th substation; β_i is transformer load factor, $S_{r,i}$ is rated capacity of transformer.

The capacity of the transformer substations should be sufficient to cover the city consumers' load. To ensure power supply, all electricity consumers should be distributed between the substations, thus forming appropriate service areas. As some transformer substations' service areas overlap, compliance to the following condition should be controlled:

$$\Pi_{city} \le \sum_{i=1}^{n_{TS}} \Pi_{TS,i} \cdot k_{overl} \ , \tag{2.7}$$

where k_{overl} is transformer substations service areas overlapping coefficient.

The service area of each individual substation depends on the load density in this area and the substation load, which in its turn depends on the transformer rated capacity, the number of transformers in the substation and the transformer's load factor:

$$\Pi_{TS,i} = \frac{S_{TS,i}}{\sigma_i} = \frac{n_i \beta_i S_{r,i}}{\sigma_i} \ , \tag{2.8}$$

where σ_i is load density in the service area of the *i* –th substation.

In case the load density in the city or service area of a substation is known or assumed the total load can be obtained using (2.5) or (2.8).

The latter method has been recognized as the most convenient one, and load density has been taken as the key indicator for further analysis. The average load density in the city and substation service areas vary depending on the type of territory development, but the data on load densities in some areas of the city of Riga and service areas of transformer substations is lacking. Moreover, the load density is the variable that changes as the substations' loads increase or decrease, so the load density should be identified or adjusted time after time. The load density was determined in some districts of city under the Contract with JSC „Latvenergo". The further developments regarding this subject were made within the framework of this Thesis and are represented in chapter Four [3, 6, 10, 12, 27].

3. SERVICE AREAS AND SERVICE RADII OF THE TRANSFORMER SUBSTATIONS

3.1. Modelling of a transformer substation's service area

City power supply system is a hierarchical structure. The levels of this structure are made up by subsystems: the external power supply with a voltage of 330 kV (or higher), the internal power supply system with voltages of 110-20-10-0.4 kV and the consumers. Historically, certain hierarchy of voltages and the corresponding load density hierarchy have formed [5, 9, 10]. The hierarchical structures are shown in Figure 3.1.

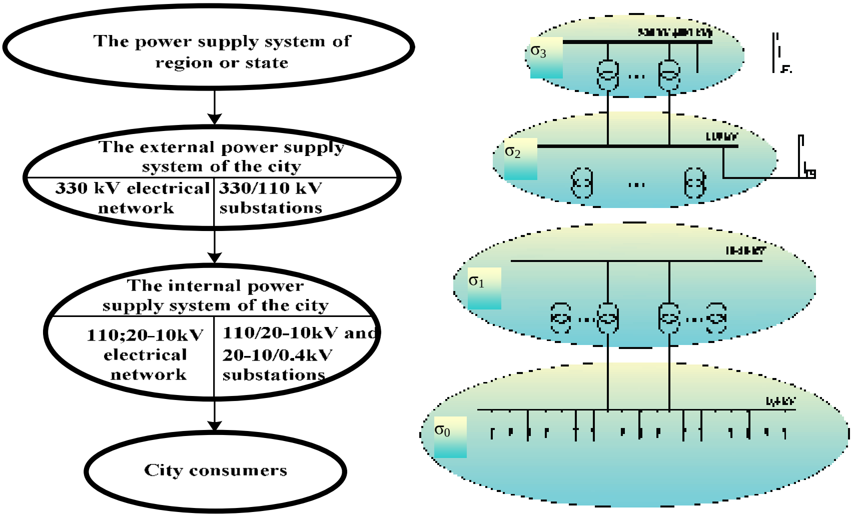


Fig. 3.1. Hierarchical structures of the Riga city power supply system

To ensure rational development of each subsystem and the power supply system in total systemic approach principles should be used. This means that the subsystems should be viewed as a single object, which should be developed in a continuous manner according to uniform principles. The systemic approach principle has been implemented in comprehensive formation of different

voltage networks, as similar modelling approach for all subsystems was applied.
The selected model of the substation service area should be applicable and practical for any voltage transformer substation and any form of built-up area. The transformer substations service areas should cover the territory of the city so that the consumers are distributed between the substations in the most efficient manner.
For the model of a service area a variety of geometric shapes can be used: circle, square, regular hexagon. Hexagonal form has been accepted as a geometric model of a service area as this is the most convenient shape, which is capable of covering virtually any form of built-up area [2, 9, 10, 12, 14, 18].
In Figure 3.2 in graphic form the service areas of 330/110 kV, 110/20-10 kV and 20-10/0.4 kV transformer substations of the city power supply system are shown. It’s been assumed that the substation is located in the centre of the hexagon, but in real conditions, it should not be outside the hexagon limits. The transformer substations of each voltage have got its own service area with adequate load density. Therefore, for example, the number of 20-10/0.4 kV transformer substations varies in equal service areas of 110/20-10 kV.

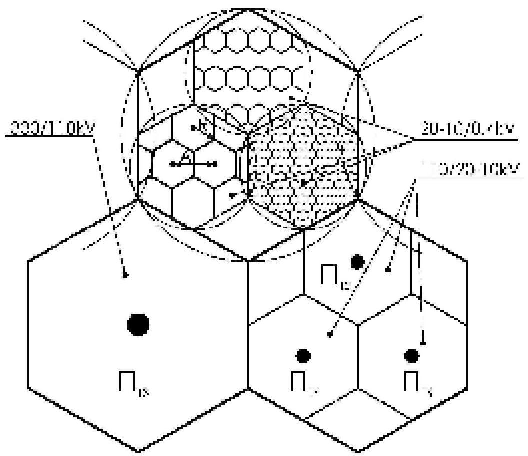


Fig. 3.2. The ideal model of service areas for transformer substations of 330/110 kV, 110/20-10 kV, 20-10/0.4 kV voltage levels

Using the accepted hexagonal model of service areas the mathematical relations between the basic dimension of the service areas and dependencies between the basic dimensions of the service areas and technical characteristics of different voltage transformer substations were obtained, taking into account the expression in (2.8):

$$\Pi_{TS,i} = 3\sin\left(\frac{p}{3}\right)\cdot R_i^{\,2} = 2.6\cdot R_i^{\,2} = 3.46\cdot r_i^{\,2} = \frac{n_i\, b_i\, S_{r,i}}{s_i};$$

$$R_i = 0.62\cdot\sqrt{\Pi_{TS,i}} = 0.62\cdot\sqrt{\frac{n_i\, b_i\, S_{r,i}}{s_i}}; \qquad (3.1)$$

$$r_i = 0.54\cdot\sqrt{\Pi_{TS,i}} = 0.54\cdot\sqrt{\frac{n_i\, b_i\, S_{r,i}}{s_i}};$$

$$A_i = 2\, r_i = 1.1\cdot\sqrt{\Pi_{TS,i}} = 1.1\cdot\sqrt{\frac{n_i\, b_i\, S_{r,i}}{s_i}},$$

where $\Pi_{TS,i}$ is a transformer substation's service area; R is the radius of the circle enclosing the hexagon, or the radius of the substation service area (service radius) and a side of the hexagon; r is the radius of the circle enclosed by the hexagon; A is a theoretically least accepted clearance between to neighbouring transformer substations. The chosen model of the service area determines the ideally minimum length of high-voltage lines ensuring connection between existing substations and their hook-up to existing networks. The higher is the transformer substation voltage and the installed capacity of its transformers, the bigger should be the substation service area and the longer the connection lines of the new substations.

The dependencies of 330/110 kV, 110/20-10 kV transformer substations' service areas and their radii on the load density acquired using the resultant mathematical expressions are shown in the Figures 3.3-3.8 in the form of histograms for permissible load factors of transformers β_{perm}=0.5 or β_{perm}=0.7.

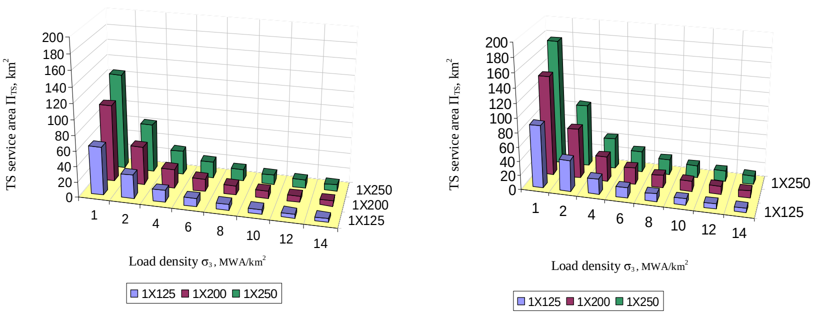


Fig. 3.3. The dependency of 330/110 kV one-transformer substation's permissible service area on the load density in the form of a histogram for β_{perm}=0.5 and β_{perm}=0.7

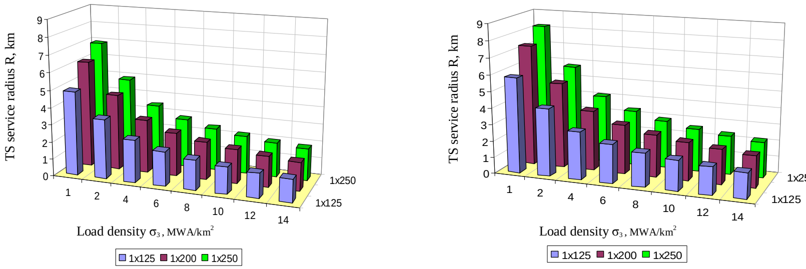


Fig. 3.4. The dependency of 330/110 kV one-transformer substation’s permissible radius on the load density in the form of a histogram for $\beta perm$=0.5 and $\beta perm$=0.7

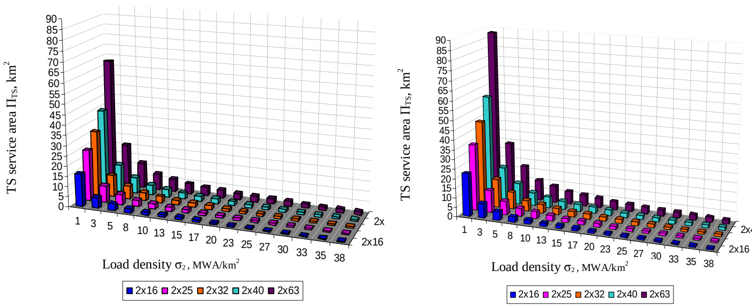


Fig. 3.5. The dependency of 110/20-10 kV two-transformer substation’s permissible service area on the load density in the form of a histogram for $\beta perm$=0.5 and $\beta perm$=0.7

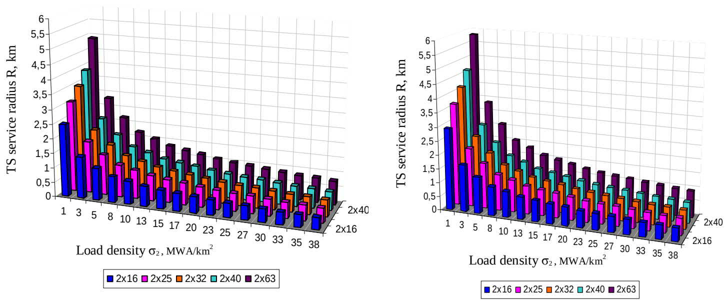


Fig. 3.6. The dependency of 110/20-10 kV two-transformer substation’s permissible radius on the load density in the form of a histogram for $\beta perm$=0.5 and $\beta perm$=0.7

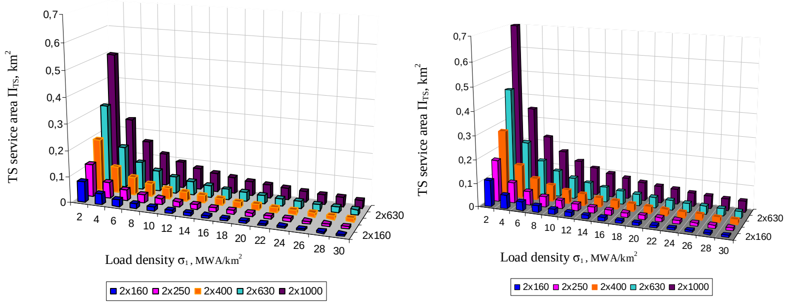


Fig. 3.7. The dependency of 10-20/0.4 kV two-transformer substation’s permissible service area on the load density in the form of a histogram for $\beta perm$=0.5 and $\beta perm$=0.7

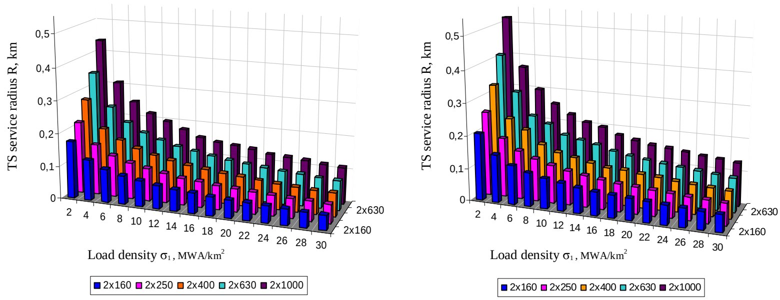


Fig. 3.8. The dependency of 10-20/0.4 kV two-transformer substation’s permissible radius on the load density in the form of a histogram for $\beta perm$=0.5 and $\beta perm$=0.7

From expression (3.1) and the Figures 3.3-3.8 above it can be concluded that the substation service area varies in direct proportion to the transformer rated capacity in case of constant load density and load factor values, i.e., it increases with each rated capacity scale step. The square value of the transformer substation’s service radius varies in proportion to the transformer rated capacity in case of constant load density and load factor values, i.e., in this case the dependence is weaker than with the service area. The square value of the transformer substation’s service radius varies in inverse proportion to the load density at constant transformer rated capacity and load factor values.

The accepted model of the transformer substation service area and the acquired mathematical dependencies between the basic dimensions of the model make it possible to build geometrical templates of substation service areas in hexagonal shape. The templates are effective and practical to use when distributing the city built-up territories in the city Masterplan in order to correct the existing substations’ service areas and find locations for new substations.

3.2. Changes in transformer substation service areas under operation and development of the power network

Growing load of existing consumers, appearing new consumers inside the service areas of one or more of existing transformer substations result in increasing load of transformers density and load density in these areas. It is advisable for a transformer substation to operate within the permissible service area as long as possible. If the transformer has got some reserve capacity the growing load causes forced increasing of transformers' load factor. In the absence of reserve additional transformer capacity is required to serve the increased load. There are several approaches to ensure covering of increased electrical load:

- Replacement of transformers with those having higher power ratings at one or more transformer substations;
- Increasing the number of transformers in substation;
- Construction of new substations.

The Third Chapter of the Thesis contains mathematical analysis of transformer service area changes connected with the load density increases and recommendations for keeping the service area within the permissible limits.

3.3. Dependencies of load densities at different levels of hierarchy

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 (2.6) depending on the type of development of the area, building floor number, household electrification level, consumer connection points (voltage level) to the power supply system. In case the load densities in transformer substations service areas vary considerably, the average load density urban built-up area can be determined as follows:

$$s_{av} = \frac{k_{o,j} \sum_{i=1}^{n_{TS}} S_{TS,i}}{\sum_{i=1}^{n_{TS}} \Pi_{TS,i}} = \frac{k_{o,j} \sum_{i=1}^{n_{TS}} n_i \, b_i \, S_{rate,i}}{\sum_{i=1}^{n_{TS}} \Pi_{TS,i}} = \qquad , \qquad (3.2)$$

$$= \frac{k_{o,j} \cdot \left(S_{TS1} + S_{TS2} + \ldots + S_{TS,i}\right)}{\Pi_{TS1} + \Pi_{TS2} + \ldots + \Pi_{TS,i}}$$

where $S_{TS,1},..,S_{TS,i}$ is full load of the i–th substation in specific year; j – hierarchy level of voltage; $\Pi_{TS,1},..,\Pi_{TS,i}$ is service area of the *i*-th substation, km^2. Actual load densities for each voltage level are different and create a hierarchy of load densities in accordance with the voltage hierarchy [10.14].

Load density for each voltage level depends on the aggregate consumer load at this level, i.e.:

$$s_0 = s_{0.4} = \frac{S_{0,4}}{\Pi_{city}} ; \tag{3.3}$$

$$s_1 = s_{20-10} = \frac{S_{\Sigma\ 20-10}}{\Pi_{city}} = k_{o,1} \cdot s_0 ; \tag{3.4}$$

$$s_2 = s_{110} = \frac{S_{\Sigma\ 110}}{\Pi_{city}} = k_{o,2} \cdot s_1 ; \tag{3.5}$$

$$s_3 = s_{330} = \frac{S_{\Sigma\ 330}}{\Pi_{city}} = k_{o,3} \cdot s_2 , \tag{3.6}$$

where $S_{\Sigma\ 0,4}$, σ_o is consumer load and load density at 0.4 kV level; $S_{\Sigma\ 20\text{-}10}$, σ_1 is consumer load and load density at 20-10 kV level; $S_{\Sigma\ 110}$, σ_2 is consumer load and load density at 110 kV level; $S_{\Sigma\ 330}$, σ_3 is consumer load and load density at 330 kV level; $k_{o,1}$ is 20-10/0.4 kV transformer maximum load simultaneity factor depending on the number of transformer substations of the respective voltage network, assumed as 0.85; $k_{o,2}$ is 110/20-10 kV transformer maximum load simultaneity factor depending on the number of transformer substations of the respective voltage network, assumed as 0.9; $k_{o,3}$ is 330/110kV transformer maximum load simultaneity factor depending on the number of transformer substations of the respective voltage network, assumed as 0.95.

On the basis of (3.3-3.6) the actual load densities in the transformer substation service areas vary depending on the voltage level and are different from the average load density in the city. In this connection actual service areas of transformer substations in the city territory considerably differ.

4. DEFINING OF 110/10-20 KV TRANSFORMER SUBSTATION PERSPECTIVE LOADS AND THEIR DISTRIBUTION OVER THE CITY TERRITORY

4.1. Defining of 110/10-20 kV transformers substation load for perspective to year 2020

In 2005 – 2006, in the pre-crisis Riga the situation developed to critical. There was approximately 300 MVA load demand prospective, which couldn't be connected to the existing grid.

As the Thesis was started in 2007, forecasts and solutions were developed for the favourable economic and energy development conditions. The author of the Thesis has actively participated in development of Riga 110 kV high-voltage network for the time period until 2020 within the framework of Contracts with JSC "Latvenergo" [26, 27]. Developments for selection of the prospective power supply system were started in 2007 on the order of JSC "Latvenergo". One of the purposes of working out was rational placement of prospective load centers and new 110 kV substations based on the City Development Masterplan for 2006 – 2018 accepted by the Riga City Council, Riga long-term development strategy until 2025 and taking into account the planned urban territory development [29].

The situation changed in 2007 with the economic crisis. The power consumption and load decreased and many projects and construction sites were suspended. Although load growth in Riga appears to have stopped, the network must be prepared for further load increase. Therefore the scientific working out have been continued in 2008 under the above-mentioned contract and in 2009 – 2011 within the framework of this Thesis [1-7].

Considering the changes in the economic situation, a critical analysis of the results acquired in 2007 – 2008 and adjustment of calculations were made (Chapter Two of the Thesis) as well as some additional calculations were carried out. It was confirmed that the developed methodology can be used for further solution of individual tasks for urban power supply system's development as the initial data are specified.

Currently, Riga has got an established network with a fixed configuration and geographically and historically preconditioned location of substations. The distribution of consumers between the substations determines their service areas. The actual distribution of service areas in 2008 – 2010 according to the data of JSC "Latvenergo" Power Company "Augstsprieguma tikls" is shown on the Riga City map of Riga Development Plan for 2006 – 2018 prepared by the Riga City Council (see Figure 4.1). Such a distribution is sometimes lacking accurate technical and economic feasibility evaluation. Existing service areas have complex geometric shapes, moreover, the service area of each substation differs from the others. Rational planning of electric networks and locating of new substations is complexities by lack of a consequent, uniform and well-founded approach and existence of networks developed under specific historic conditions. Due to continuous load changes periodical analysis of the compliance of service areas with the permissible limits is required.

By means of collecting and analyzing data and adjustment of calculations a methodology for rational formation of an urban power supply system at each hierarchical level [2, 3, 5, 7] was developed. Implementation of the

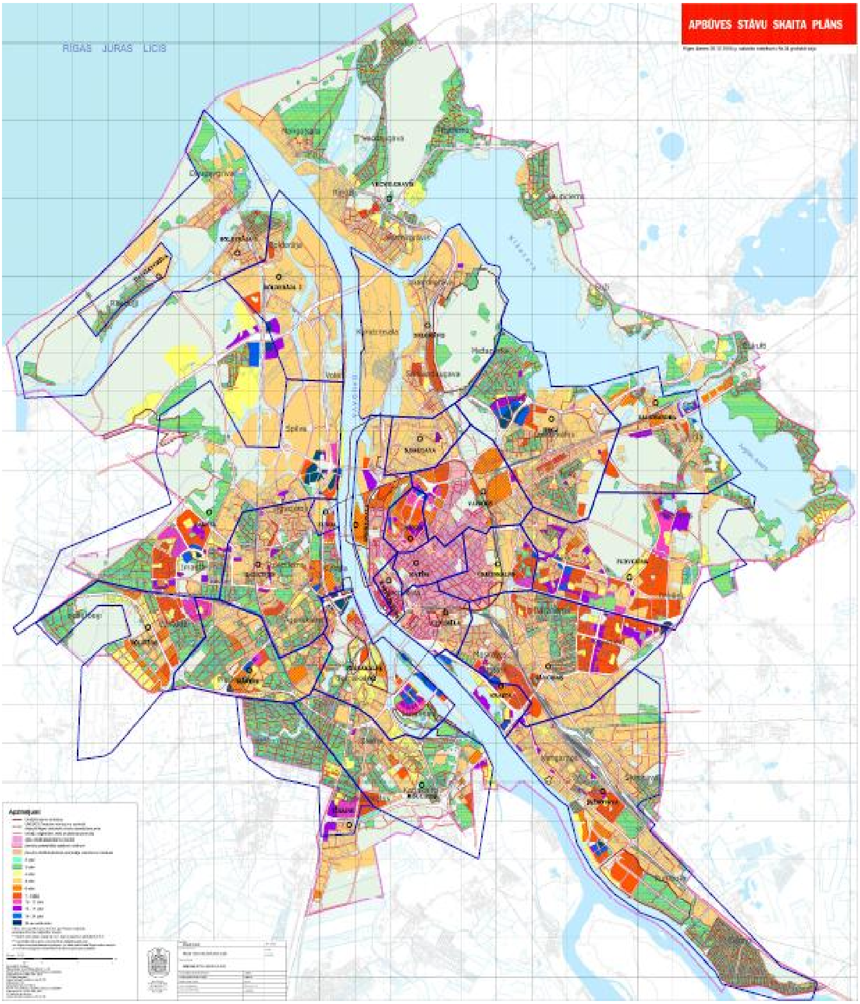


Fig. 4.1. Actual distribution of the transformer substations' service areas in the territory of Riga in 2010

methodology is viewed using as an example mostly the 110 kV network, but it is applicable also for other voltage hierarchy network levels. Subject to the theoretical forecasts of the Riga aggregate load in Figures 2.1, 2.2 and Table 2.1 the existing and new substations' prospective load was acquired for the time period until 2020 taking into account different scenarios: for favourable (in year 2007) and adverse (years 2008 – 2010) economic conditions.

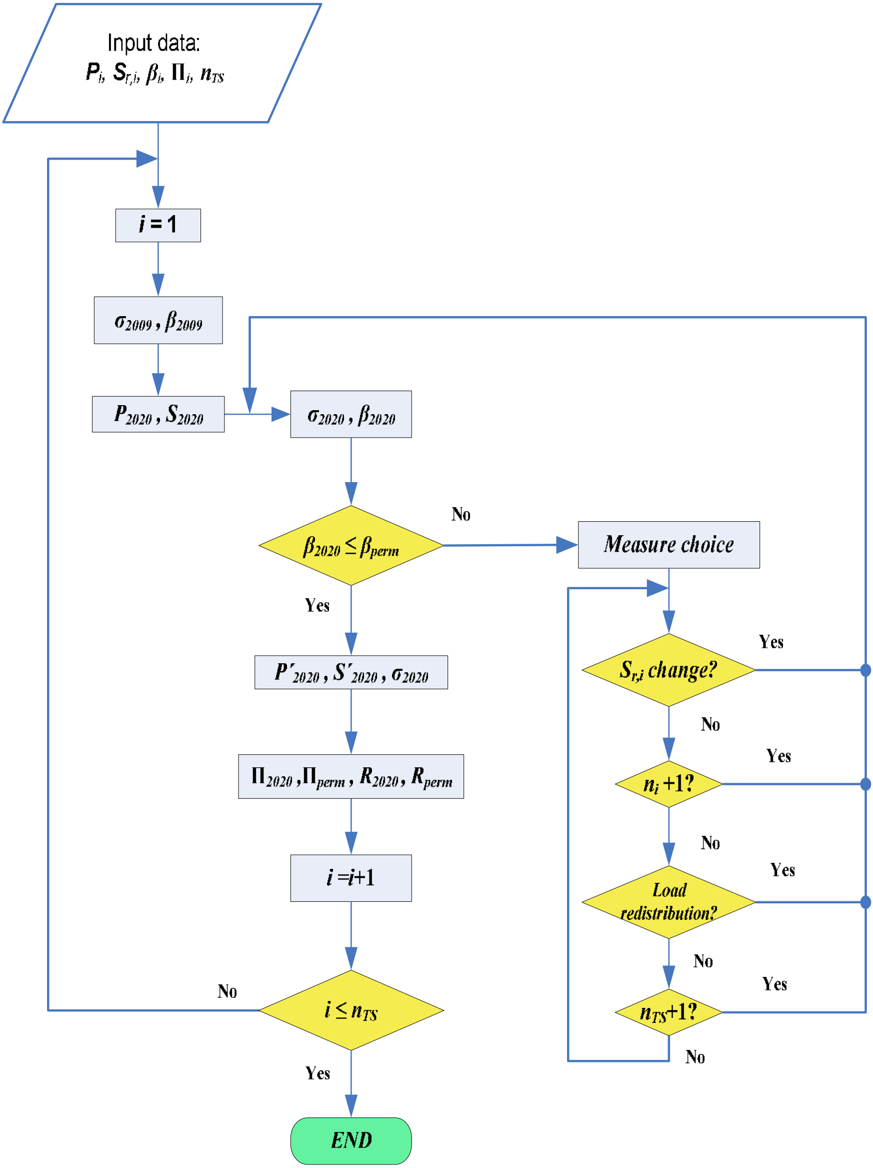


Fig. 4.2. Perspective load of a transformer substation calculation algorithm

Prospective maximum loads of transformer substations have been obtained as follows [2, 3, 7, 16]:

$$P_{2020} = P_{2008} \cdot \left(1 + \frac{a}{100}\right)^{t_2 - t_1} + k_1 \cdot k_2 \cdot P_{req} \,, \qquad (4.1)$$

where a is growth of the consumer load per year; t_1 is the load growth start year according to the assumed load growth scenario; t_2 is the last year of the estimate period (t_2 = 2020, etc.); P_{req} is the required power for the network connection according to JSC "Sadales tikls" data; k_1 is maximum load simultaneity factor, assumed 0.8; k_2 is correction factor related to the uncertainty of the data regarding the required capacity and term of the connection, assumed 0,7.

In the course of analyses for each of the transformer substations load factor is calculated, and its compliance with the permissible load factor of transformer is evaluated. In case of non-compliance it is necessary to provide one or more technical measures: reduce the load of the transformer substation by distributing its consumers between neighbouring substations, or increase the installed capacity of the transformer substation by replacing a transformer with another one having higher rated capacity, or increase the number of transformers at the substation.

Upon recalculation of the load the acquired value should be again checked for compliance with the permissible load factor. The calculation algorithm is given in Figure 4.2.

The methodology provides opportunities for geometric modelling of the actual service areas of existing and future substations and replacement them with identical hexagonal areas in order to make analysis of the situation and implement a uniform approach to the construction of service areas.

The methodology provides also opportunities for geometric modelling of the actual service areas of existing and future substations and replacement them with identical hexagonal areas in order to make analysis of the situation and implement a uniform approach to the construction of service areas.

While modelling, the size of service areas can be taken into account and adjusted, except the land unusable for development. An approach to distributing transformer substations on the Riga City Masterplan on the basis of geometrical templates (Figure 4.3) was proposed.

For automation of calculations and for graphical placing of substations the program "TASAD" was developed in Microsoft Excel environment (under the contract with JSC "Latvenergo") and later was specified and modified and also graphic software AutoCAD was used. Distribution of transformer substation in the city for different forecast scenarios is made on the basis of Riga city map (the graphic part "Planned Number of Storey’s " of the Riga City Development

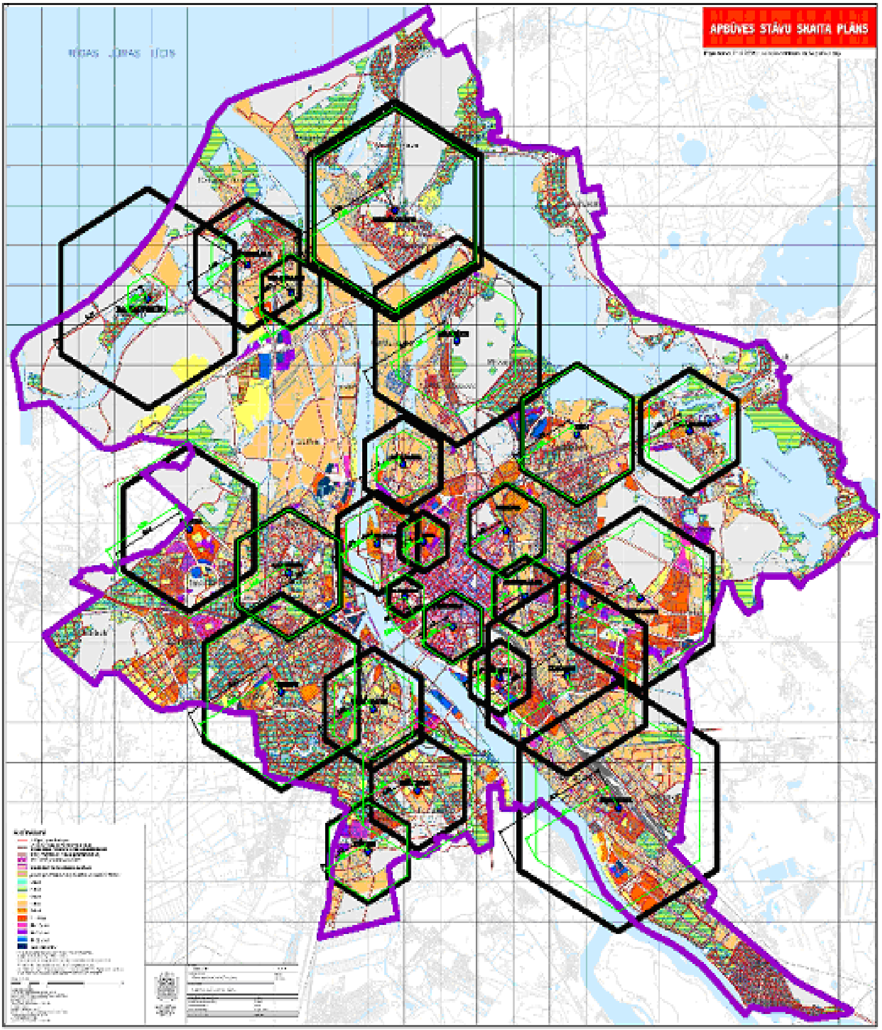


Fig. 4.3. Distribution of the actual and permissible service areas of the Riga City existing transformer substations

Masterplan for the years 2006 - 2018) or just within the boundaries of the city (Figures 4.4 and 4.5) [2,5,12,29].

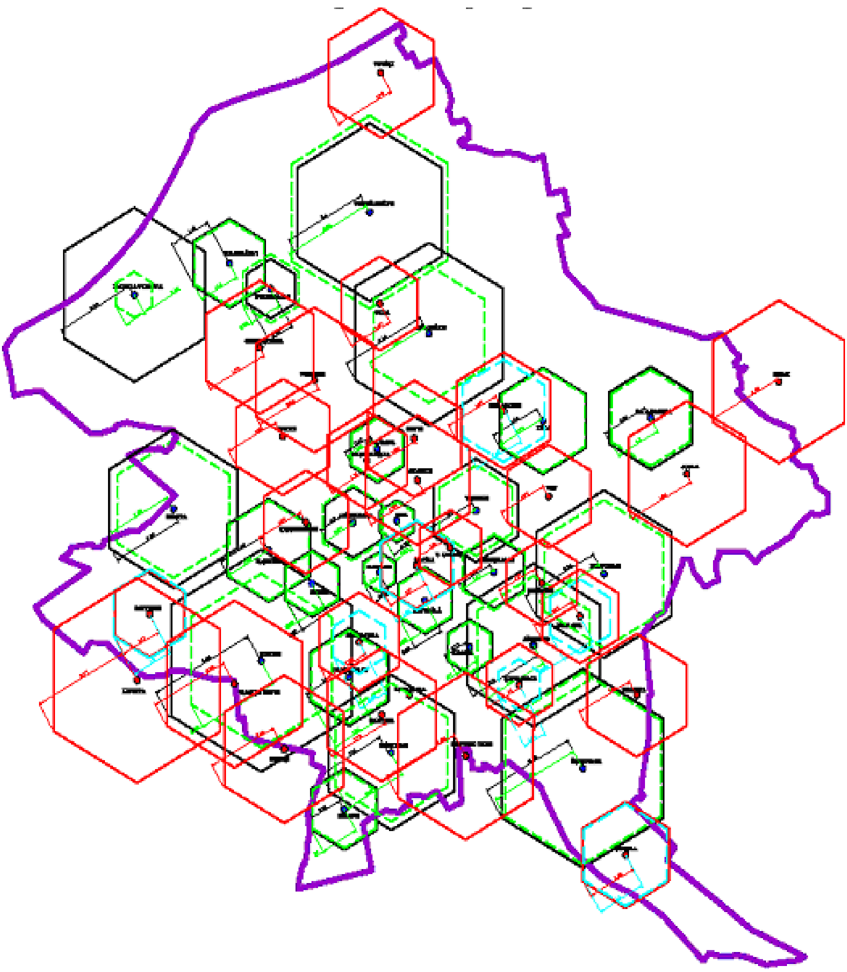


Fig. 4.4. Distribution of the actual and perspective transformer substations' service areas of the Riga City in 2020 in case of 3% of load growth per year

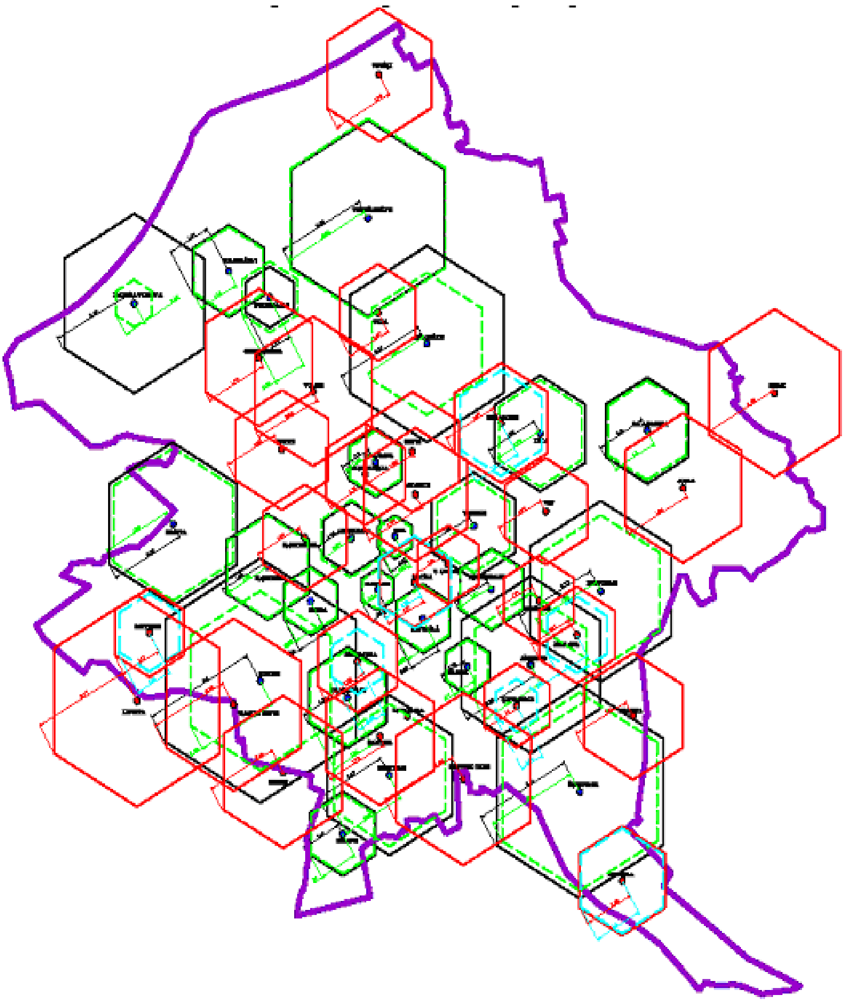


Fig. 4.5. Distribution of the actual and perspective transformer substations' service areas of the Riga City in 2020 in case of 1.5% of load growth per year

In the Figures, in black colour the permissible transformer substations' service areas are shown. Green dotted hexagons show the loading of the existing transformer substations in the maximum load conditions. In red colour the permissible service areas of the future transformer substations are indicated.

4.2. Correction of 110/10-20 kV transformer substations' loads according to the situation in 2010

Based on the data in the previous chapter, the expected load growth forecasts the load of transformers is evaluated. For the analysis the data on the 110 kV transformer substations' loading in 2010 (see Table 4.1) are used. Figure 4.6 shows the share of the maximum load of Riga city that was covered by each substation in 2010. Most of the maximum load is served by the substations: Centrals, Marupe, RTEC-1, Ilguciems, Grizinkalns, Bisuciems, Vairogs, Purvciems. The new substations Zunda and Zolitude in fact were not loaded in 2010.

The load of specific transformers was calculated on the basis of the corrected Riga aggregate load forecast for the period until 2025, though it is difficult to predict the growth rates in post-crisis period yet. The corrected forecast corresponds with the forecast shown in Figure 2.2. The load and load factor of the transformers at existing substations for the time period until 2025 in case of 3% of load growth per year is calculated and represented in Figures 4.7 and 4.8.

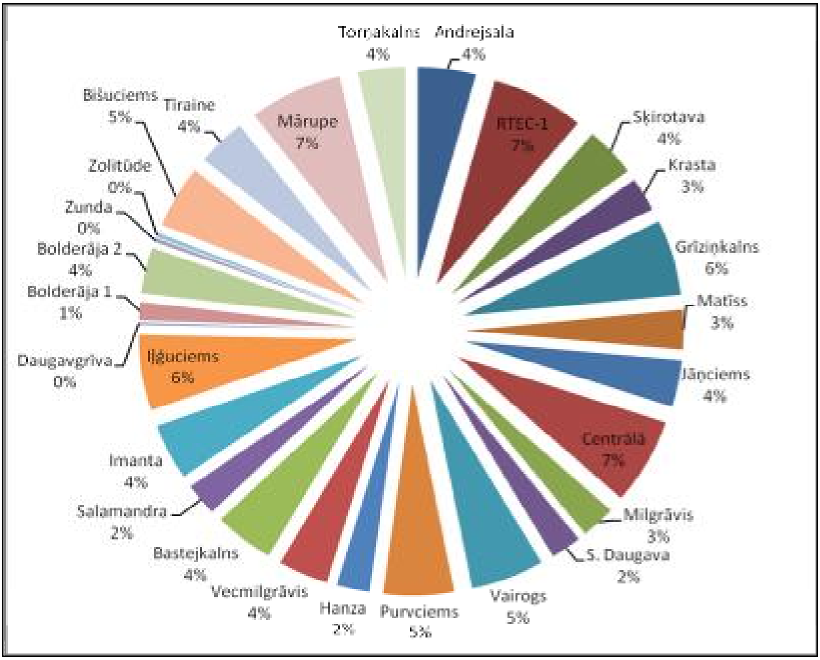


Fig. 4.6. Distribution of the Riga City maximum load between transformer substations in 2010

Table 4.1

Riga City maximum load in the time period from 2007 until 2010

No.	Name of the substation	2007 P,MW	2008 P,MW	2009 P,MW	2010 P,MW
1	Andrejsala	18.8	21.4	19.4	20.9
6	RTEC-1	29.6	30.2	29.2	33.57
18	Skirotava	20.53	21.4	18.2	18.6
101	Krasta	15.23	15.6	13.3	12.52
105	Grizinkalns	37.7	39.6	36.2	28.15
106	Matiss			0	14.55
110	Janciems	39.54	41.2	33.4	17.47
111	Centrala	34.36	36.8	33.2	32.08
112	Milgravis	15.12	14.9	11.9	12.54
113	S. Daugava	16.42	13.2	12.1	11.12
114	Vairogs	38.57	38.1	30.8	26.37
115	Purvciems	25.17	25.5	25.3	25.57
116	Hanza	15.77	16.2	15.3	11.87
117	Vecmilgravis	19.74	20.2	19.3	18
119	Bastejkalns	31.22	30.8	25.6	21.65
123	Salamandra	14.91	12.4	11.2	11.96
130	Imanta	26.04	27.4	21.4	20.97
131	Ilguciems	30.03	30.7	28.3	28.01
132	Daugavgriva	0.65	0.3	1.4	0.89
133	Bolderaja 1	7.78	7.1	7.3	6.68
136	Bolderaja 2	18.58	18.5	19.4	17.06
137	Zunda	0.54	1	1.6	1.46
139	Zolitude			9.2	1.7
140	Bisuciems	36.95	33.5	23	23.3
141	Tiraine	21.62	21.1	16.6	17.87
142	Marupe	38.68	38.6	35.5	33.62
144	Tornakalns	19.11	19.3	18	17.18
	Total load of TS	**578.4**	**580.8**	**522.1**	**485.66**
	Power system load	**1373**	**1419**	**1340**	**1336**

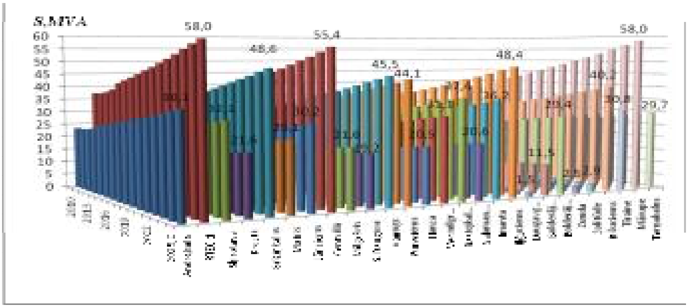


Fig. 4.7. Load of the transformers installed at Riga substations in case of 3% of load increase from 2010 until 2025

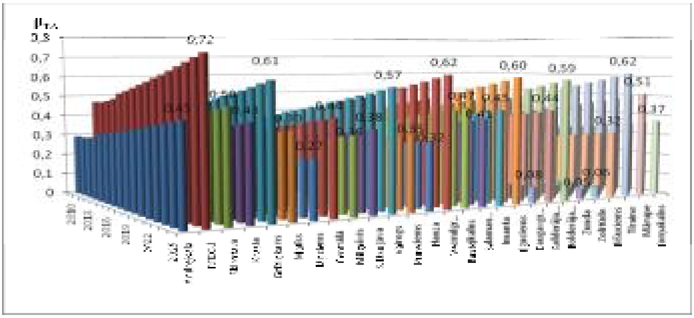


Fig. 4.8. Load factor of the transformers installed at Riga substations in case of 3% of load increase from 2010 until 2025

4.3. Correction of load density in the districts and residential areas of Riga City

Load density is an important indicator describing the city development characteristics, which can be used to determine perspective loads in city districts and to select transformer substations' power at early stages of designs when there is a lack of accurate information and detailed developments. The data of the Riga load density values is not systematized and are insufficient for urban development challenges. Therefore the author of this Thesis has specified and adjusted these data. It should be taken into consideration that load density values are quite different for the whole city and separate transformer substations service areas.

The Riga regional department of the Latvenergo JSC "Sadales tikls" has provided the data on the number of the Riga most densely built-up districts and residential areas (built-up areas, not the substations' service areas, were taken). Approximate load densities are determined for individual sectors of the city and summarized in Table 4.2:

Table 4.2

Approximate load density in the sectors of the City of Riga

District (fed from a substation)	Storey number	Maximum load current, Imax, A	Maximum load, MVA	Size of the district, km^2	Load density, MVA/km^2
Old Town (Bastejkalns)	3-6	1700	30.9	0.84	36.8
Imanta (Imanta)	5-9-12-16	1300	23.6	5.5 (3.2)	4.29 (7.4)
Plavnieki (Janciems)	9	414	7.5	0.9	8.4
Mezciems (Purvciems)	9	261	4.7	0.64	7.4
Ziepniekkalns (Bisuciems), 2 sectors	9 -12	0.12 / 0.15	2.1; 2.7	0.3; 0.36	7 ; 7.4

Notes:

1. The lowest load densities were calculated for the whole substation's areas (in brackets), the highest – for residential areas, the total area being reduced by gardens and green spaces.
2. The maximum power load has been registered based on the measurements made on the 10.5 kV busbars.

Load detection method employing average load density and size of built-up areas was used to determine aggregate load and select transformer substations' capacity for new prospective districts: Rumbula, Zaķusala and Lucavsala.

Based on the performed calculations and graphic representations in Chapter Four the following conclusion can be made:

1. In case that power supply network develops in favourable economic conditions at load growth amounting to 3% and even 1.9% most transformer substations would be overloaded in 2020 and at the time the load deficit the acute need for construction of many new substations and renovation of the existing ones will appear.
2. The calculated transformer substations' load forecast correction made in 2008 – 2010 shows that the forecast values for 2020 will probably not be achieved (the city load in 2010 according to the measurements was 485 MW instead of 631 MW according to 2006 forecast), and achievement of the calculated values is expected no earlier than in 2025 – 2030.
3. Upon analysis of the transformer substations' prospective loads a conclusion was made that by 2020 the following new 110 kV substations could be constructed: Kengarags, Osta, Voleri, Mezaparks, Skanste, Deglava, and Rumbula (provided that there is a new residential complex built).
4. The calculations need to be further adjusted as new data are received.

5. DEFINITION OF 110 KV SUBSTATIONS' TRANSFORMER OPTIMUM CAPACITY AND DEVELOPMENT OF THE RIGA CITY PERSPECTIVE POWER SUPPLY NETWORK SCHEME FOR THE TIME PERIOD UNTIL 2020

5.1. Defining of 110 kV substation transformer optimum capacity

To rationally form a city power supply system, the data of transformer installed capacity should be known at the early stages of development designs. When developing the city power supply scheme with 10-15 year perspective directive materials, generalized indicators of the industry and networks, utility companies and city development plans can only be used, i.e., the optimum installed capacity of transformers is to be selected in the conditions of incomplete and uncertain source information. Mathematical models connected with obtaining extremum are difficult to use to define optimum parameters, and most commonly comparison of options is applied. The received results have approached character and should be corrected as soon as new information is received and development plans are specified.

Under the Contract with JSC "Latvenergo" with the author's participation a mathematical model for evaluation of the optimum transformer installed capacity in city or its districts was developed. As the optimality criterion a minimum of total capital investments was selected. In the event that the substation transformers have equal installed rated capacities, average load density σ_{av} in the substations' service areas may be taken [41, 45, 46]. In this case, expressions (2.1) and (2.5) look as follows:

$$S_{city} = k_{o,2} \cdot n_{TS} \cdot S_{TS,i} \quad , \tag{5.1}$$

and

$$S_{city} = s_{av} \cdot \Pi_{city} \quad . \tag{5.2}$$

Based on (5.1) and (5.2) for equal values the following can be obtained:

$$\Pi_{city} = \frac{S_{city}}{s_{av}} = \frac{k_{o,2} \cdot n_{TS} \cdot S_{TS}}{s_{av}} = k_{o,2} \cdot n_{TS} \cdot \Pi_{TS} \tag{5.3}$$

Then, the number of transformer substations in the city area provided that there are similar transformers installed in them, should be the following:

$$n_{TS} = \frac{S_{city}}{k_{o,2} \cdot S_{TS}} = \frac{S_{city}}{k_{o,2} \cdot s_{av} \cdot \Pi_{TS}} = \frac{\Pi_{city}}{k_{o,2} \cdot \Pi_{TS}} \tag{5.4}$$

Service areas Π_{TS} were calculated according to the installed capacity of transformer substation, given in Chapter Three (Table 3.3). The maximum permissible transformer load factor accepted for calculations is β_{perm}=0.5 in normal conditions for two-transformer substations. At other load factors the service areas are calculated by the expression (3.1).

Evaluation of perspective 110/10 kV substations' optimum capacity in the cities depending on the load density was carried on the basis of comparison of development options. Mathematical model takes into account the mutual correlation between the 110 kV and 10 kV network parameters.

Function K_{Σ} of total capital investment for different network construction options include: capital investments for construction of 110/10 kV transformer substations, 110 kV cable lines for connecting 110/10 kV transformer substations, 10/0.4 kV transformer substations, 10 kV cable lines for connecting the 10/0.4 kV transformer substations:

$$K_{\Sigma} = K_{\Sigma}(S_{TS}, s_{o,2}) = K_{TS\Sigma} + K_{HL\Sigma} + K_{TP\Sigma} + K_{ML\Sigma}, \qquad (5.5)$$

where $K_{TS\Sigma}$ is capital investment in construction of 110/10 kV transformer substations; $K_{HL\Sigma}$ is capital investment in construction of 110 kV cable lines for connection of 110/10 kV transformer substations; $K_{TP\Sigma}$ is capital investment in construction of 10/0.4 kV transformer substations; $K_{ML\Sigma}$ is capital investment in construction of 10 kV cable lines for connection of 10/0.4 kV transformer substations.

Within the Thesis power supply system objective function based on the total capital investment (5.5) has been specified and corrected [2, 6].

The criterion for choosing of 110/10 kV transformer substation optimum capacity is total investment minimum of the power supply system. Due to incomplete and uncertain information on the sequence and terms of the object construction, the net present value criterion, maintenance, depreciation costs and losses were not used in the estimates. There is a possibility that construction of some substations would not be needed until 2020 thanks to indefinite and varying load growth in different areas of the city.

Calculations were made for function (5.5) taking into consideration each component's dependence on changing parameters, and using the developed [27] and adjusted in this Thesis calculation application in Microsoft Excel environment.

From the calculation results (Figure 5.1) it can be concluded that for the cities with territory 148 km^2, taking into consideration city load density, the transformer substations with the following transformer capacities are the most beneficial: for load density $3 \leq \sigma \leq 5$, MVA/km^2, – substations with 2x32 MVA transformer capacity, for load density $7 \leq \sigma \leq 9$, MVA/km^2 , – 2x40 MVA substations, for load density $11 \leq \sigma \leq 15$, MVA/km^2 , – 2x63 MVA substations.

Having the data on the optimum capacity of the transformer substation, using formulas (3.1) the following optimum network parameters can be obtained: service area, service radius, minimum distance between the neighbouring substations. Then geometric templates for distribution of substations in the City Master Plan can be constructed.

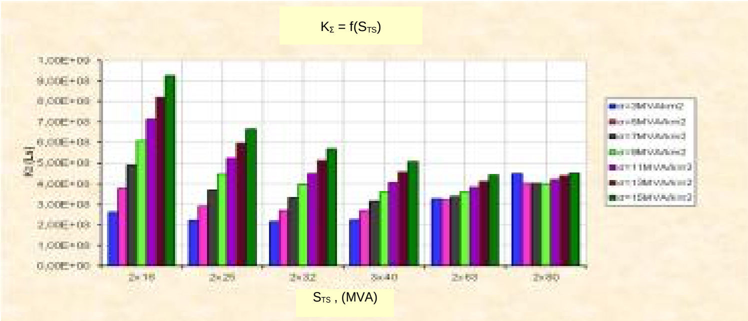


Fig. 5.1. Dependency of the total capital investment in power supply system on the substation transformers' capacity $K_{\sum}=f(S_{TS})$ in the form of a bar chart

5.2. Development and evaluation of the Riga City 110 kV network scheme

In 2008, as the research of Riga high-voltage network was continued five options for the Riga city electrical networks were developed with the direct participation of the author of this Thesis. During the JSC "Latvenergo" Expert Council meeting on the 2nd February 2009 the proposed five options were discussed by the JSC „Augstsprieguma tikls” and JSC „Sadales tikls” experts and the 1st option was adopted as the basis for Riga City perspective 110 kV network scheme for the period until 2020 (Figure 5.2 and 5.3). When developing the scheme a possibility to include 25 new 110 kV substations in the existing network was foreseen to cover load growth in urban areas and probable appearance of large load consumers. Development and adoption of this network scheme is a very important step for consistent development of the city. The network diagram is crucial for development of the city power supply system in order to ensure the power supply sufficient for a modern city, taken both existing customers and new ones that are going to be connected to network [2, 5, 7, 27].

During the JSC "Latvenergo" Expert Council meeting on 15 January 2010 the scheme shown in Figure 5.4 as Option 2 was adopted. To ensure Riga City power supply system development scheme provides for 23 new 110/10-20 kV substations and existing or new 110 kV lines to connect these substations to the network.

During Expert Council meeting on 15 January 2010 some ambiguous solutions were mentioned that are located at the following points of the scheme (accepted as Option 3 in Figure 5.5):

- connection of the 110 kV substation Spilve to the 330/110 kV substation Imanta or the 110 kV line Imanta – Daugavgriva;

- construction of the third 110 kV line from the substation Centrala to the substation Krasts or Zemitani;
- the second 110 kV connection to the substation Rumbula might be made 110 kV substations RTEC-2 or Salaspils.

Considering the above-mentioned one sub-option that would take into account the eventual changes in the network diagram adopted by JSC „Latvenergo” was reviewed.

The following conditions were assumed for calculations:

1) Capital investments in development of 330 kV network are similar for all the options therefore they are not taken into consideration in comparison.
2) The average cost of construction of a 110 kV two-transformer substation (two transformers, two cubicles for transformer connection, two cubicles for line connections) is 4.2 million lats (according to JSC "Latvenergo" Research and Development Department recommendations); the cost of 1 km of cable line is 700 hundred lats, the cost of one 110 kV traditional design cubicle is 400 hundred lats, new technology design cubicle – 800 hundred lats (according to JSC "Latvenergo" Research and Development Department recommendations).
3) In Table 5.1 the costs of new technology design and traditional (in brackets) 110 kV cubicles are given.
4) The assumed capital investment in river crossing is higher by 10% than the investments in buried cable lines.

Fig. 5.2. 110 kV network of Riga development option 1

Fig. 5.3. Idealized scheme of Riga 110 kV network option 1

Fig. 5.4. Riga 110 kV perspective scheme for the time period until 2020 (Option 2)

Fig. 5.5. Riga 110 kV perspective scheme for the time period until 2020 (Option 3)

Table 5.1

Evaluation of prospective options for 110 kV network scheme

Parameters	Option 1	Option 2	Option 3
Total number or 110 kV substations, pc.	28	23	23
Capital investments in construction of 110 kV substations, mil. LVL	117.6	96.6	96.6
Total length of prospective 110 kV cable lines, km	91.5	78.3	94.4
Number of river crossings	3	3	3
Capital investments in construction of 110 kV cable lines, mil. LVL	64.3	55.27	61.15
Total number of new cubicles	25	26	26
Capital investments in cubicles of modern technology (or traditional design), **mil. LVL**	20.0 (10.0)	20.8 (10.4)	20.8 (10.4)
Total, mil. LVL:	**201.9 (191.9)**	**170.0 (162.3)**	**178.6 (168.1)**

According to the calculation results the total capital investments in complex implementation of the adopted perspective network scheme for the 2nd and the 3rd option are lower than for the 1st option due to differences in the number of transformer substations. The planned in 2007 – 2008 substations Matiss and Zolitude have changed their status to an "existing" one. There is no need for construction of some substations due to load decrease. It should be noted that the accepted cost of construction of transformer substation 4.2 million lats, is at 2008 values and needs adjustment due to inflation.

5.3. Main stages of methods of 110 kV network formation at its development

During elaboration of this Thesis the main stages of methods of 110 kV network formation at development conditions were reviewed and specified. These stages make up the structure of the methodology. The main stages of the methods are shown in Figure 5.6. A more detailed description of each stage is given in Chapters 2 to 5 of the Thesis.

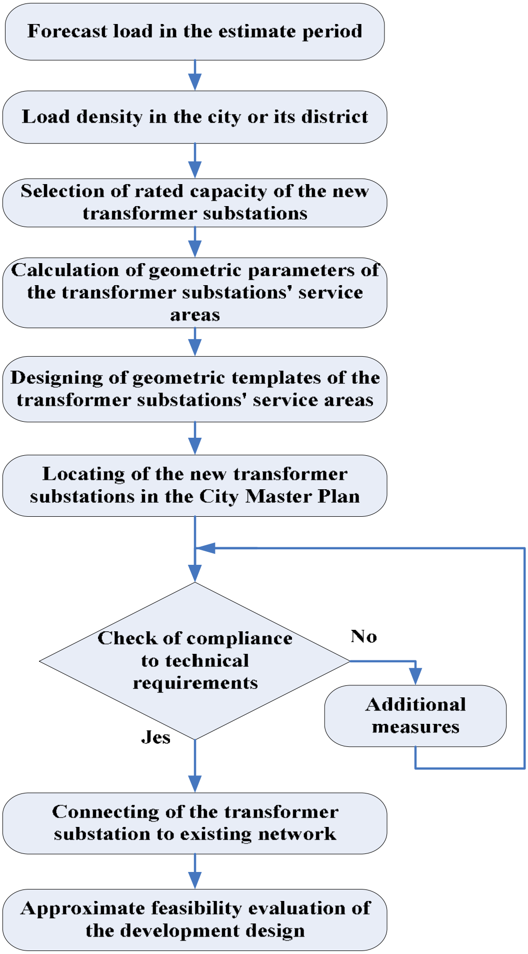


Fig. 5.6. The structure of methods of 110 kV network formation at its development

GENERAL CONCLUSIONS

1. Systemic approach to formation of an urban power supply system is based on system integrity, unity and developability principles.
2. Corrections of forecasts of Riga City load until 2020 and definition of perspective 110 kV transformer substations' loads taking into account the unstable situation in national economy and energy sector have been made.
3. Modelling principle on the basis of hexagonal geometrical templates and mathematical correlations between network parameters was applied for all the hierarchical levels of the power supply system.
4. Load densities in city districts were found or specified and on their basis optimum capacities, service areas, radii and other parametrs of 110/10-20 kV transformer substations required for rational development of urban power supply scheme were obtained.
5. An approach to distribution of transformer substations on the City Development Masterplan using the geometrical templates of transformer substations' service areas was proposed, for which calculation application „TASAD" in Microsoft Excel environment and graphic software AutoCAD were used.
6. The proposed methods has been approved and applied in practice for development of Riga City perspective power supply scheme for the time-period until 2020 within the framework of two Riga Technical University and JSC „Latvenergo" contracts: No.L7280 (No.010000/07-200dated 16.05.2007) and No.L7310 (No.010000/09-16 dated 15.01.2008). One of the power supply network development options proposed by the author of the Thesis was accepted at JSC „Latvenergo" Expert Council on January 2010 as a basis for the network to be formed in the future.
7. The elaborated methods makes it possible to identify and adopt a rational solution at the early stages of development designs in the conditions of incomplete and uncertain data, which would enable consistent and purposeful development of urban power supply system.

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