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TOWARDS THE OPTIMIZATION OF OVERHEAD POWER LINES

Summary of doctoral thesis

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Rīga 2014

UDK 621.315(043.2)
Be 565 t

Beryozkina S. Towards the optimization of overhead power lines. Summary of doctoral thesis.-R.:RTU, 2014.-39 p.

Printed in accordance with decision No. 6/14 of RTU Doctoral Board P-05 (Power and Electrical Engineering) dated March 17, 2014

EIROPAS SOCIĀLAIS FONDS
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This work has been supported by the European Social Fund within the project «Support for the implementation of doctoral studies at Riga Technical University».

ISBN 978-9934-10-534-0

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 17th of April 2014 at Faculty of Electrical Engineering of Riga Technical University, 1 Kronvalda boulevard, in room 117.

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

Svetlana Beryozkina …………………………….(signature)

Date: ………………………

The present thesis has been written in the Latvian language; it comprises an introduction, four chapters, conclusions and recommendations, a bibliography and twelve appendices. The total amount of the thesis is 170 pages in computer typesetting, which contains 65 figures and 14 tables as well as 12 pages of appendices. The bibliography lists 154 sources of literature.

CONTENTS

THE IMPORTANCE OF THE ISSUE

The present-day development of the electric energy industry, the main goal of which is to ensure uninterrupted and standard-compliant supply of electricity to consumers, is based on the emergence of powerful, multi-branched power systems, which encompass large power plants, internal and intersystem power transmission lines (PTLs) and a wide distribution network. As can be seen, one of the main elements of power systems is overhead power lines (OHLs), the role of which in the development of the future power industry is increasing at a high rate, since the expansion of the power network (PN) will be needed both country-wide and internationally.

The demand for electricity is growing steadily, therefore, considering that in 2030, all the currently planned cross-border connections will be in use, for example, Estlink-2 (connecting Estonia and Finland in 2013), NordBalt (connecting Lithuania and Sweden, after 2014), LitPol (connecting Lithuania and Poland, after 2015) and the ”Kurzemes Ring” project (2018), it is already necessary to develop, implement and apply at the existing power transmission networks (PTNs) new technologies since the implementation of the new electrical connections, the significant impact of renewable power resources (wind and solar power plants), the liberalization of the energy market and the construction of nuclear power plants (NPPs in Kaliningrad, Visaginas and Belarus) will result in a significant increase in the transit power flow loading of the Baltic transmission networks. Also, it has to be pointed out that a high percentage of all the PTLs that are currently in operation have been constructed 40...60 years ago, which is an indication of the PTN being outworn and obsolescent, which in turn requires introduction of additional renewing measures. This results in the emergence of many purposeful tasks, which are directly related to the increasing of the capacity of power networks, by ensuring reliable and high-quality power supply to the consumers.

In view of the above considerations, it becomes topical to solve the discussed problems by promoting the possibilities to ”artificially” incrase the throughput capacity of power networks by offering and implementing a number of high-voltage power line optimization methods, which have been formulated and developed within the present thesis. By using the developed technical and economic solutions, it will be possible to increase the capacity to be transmitted over the existing OHLs and those under design (determination of the hidden capacity reserve), by precisely and speedily adopting the correct decision at various cases of existing PTN problems, resulting in minimization of capital investments.

THE GOAL AND THE TASKS SOLVED BY THE THESIS

The goal of the present thesis is to increase the economic efficiency of the power system and their reliability level as well as to diminish any harmful environmental impact.

In order to reach the defined goal, the thesis **solves the following tasks**:

1. The main parameters of high-voltage power lines that impact the electric power transmission capacity, have been analyzed; also, there is a review of the methods and tools for increasing the throughput capacity of the OHL.
2. An algorithm for monitoring OHL allowable load current has been synthesized, which makes it possible to increase the throughput capacity of the existing lines in most modes practically without additional capital investments.
3. For verifying the existing OHL conductor temperature and load current evaluation methods, experimental measurements were conducted in a number of high-voltage line operation modes, which enabled the selection of the most appropriate method for the local climatic conditions.

4. The possibilities of using high-temperature conductors with composite core and their efficiency have been analysed for the local climatic and economic conditions.
5. The statement of the multicriterial OHL optimization task has been substantiated by using Pareto's approach and the scenario approach for the adoption of the final decision.
6. Calculations of the line conductor temperature and load current for the "Kurzeme Ring" project 110 and 330 kV lines have been conducted at the given OHL loading, as well as calculations of the electrical and magnetic field parameters and recommendations for selecting the conductors have been developed.
7. An OHL capital investment distribution method has been synthesized, which is used by enterprises owned by different shareholders.

THE RESEARCH TOOLS AND METHODS

1. For measuring the parameters of high-voltage line conductors and weather conditions, modern metering devices have been used: a thermovision equipment – *FLIR ThermaCAM P65* [1]; a cable height meter and thermohygrometer, *Testo 635-1*, and a pocket weather tracker, *Kestrel 4000* [2].
2. For the calculations of line parameters, specialized software complexes have been used: *PLS-CADD* [3] and *SAPR LEP* [4].
3. To formulate and solve the line parameter technical and economic optimization task, methods of the static decision theory [5]-[10], game theory [11] – [13], and cooperative game theory have been used.
4. To evaluate the environmental impact, concepts and calculation algorithms from the electromagnetic field theory have been used.
5. For the selection of line parameters, standards valid in Latvia [14]-[21], the European Union [22] and Russia [23] have been used.

THE SCIENTIFIC NOVELTY OF THE THESIS

1. By using the concept and tools of the smart grid (smart meters, fast and reliable communication channels), a synthesized high-voltage line allowable load current monitoring algorithm is proposed, which makes it possible to increase the throughput capacity of the existing OHLs in the majority of modes.
2. The conducted experimental measurements for real-life OHLs at various modes makes it possible to significantly fine-tune the existing methodologies and algorithms for evaluating the conductor temperatures and load currents of the existing high-voltage lines.
3. The proposed use of elements of the cooperative game theory makes it possible to found coalitions of various enterprises during the construction of OHLs. The existence and rationality of conditions for the foundation of such coalitions has been proved.
4. The rationality of using a multi-criterial approach to task solution has been proven. Singling out the set of Pareto decisions makes it possible to evaluate the costs of improving the environmental impact indicators and aids the adoption of well-grounded decisions.

THE PRACTICAL APPLICABILITY OF THE DOCTORAL THESIS

1. The analysis of the possibilities for using high-temperature conductors, the results of the electrical and magnetic field calculations, the conductor temperature and load current

calculation results as well as the results of solving the conductor optimization task were used in substantiating and designing a significant power facility within the transmission system infrastructure of Latvia and the Baltic states – the ”Kurzeme Ring” project (action 1), which includes the construction of 330/110 kV OHLs.
2. The investment distribution method and algorithm substantiated in the thesis can be used for founding coalitions of power and communication enterprises and diminishing the total capital investments.

THE PERSONAL CONTRIBUTION OF THE AUTHOR

The task of high-voltage line optimization has been chosen as the main direction of the paper with the help of Professor Edvins Vanzovichs. The formulation of the multicriterial task and the application of the cooperative game theory has been offered in close cooperation with Professor Antans Sauhats. The experiments have been conducted together with the experts of JSC ”Latvijas Elektriskie Tīkli”.

All the calculations, collection and summarization of input data, verification of the results, conclusions belong personally to the author.

APPROBATION OF THE DOCTORAL THESIS

1. The possibilities of applying high-temperature conductors, the results of electric and magnetic field calculations, the results of the calculations of conductor temperatures and load currents as well as the recommendations for the layout of the towers have been discussed, a number of times, with the experts of JSC ”Latvijas Elektriskie Tīkli” and JSC ”Siltumelektroprojekts” (the general designer of the ”Kurzeme Ring” project).
2. The obtained results have been reflected in the State research programme project „Innovative technologies for the acquisition and use of energy resources and ensurance of low carbon emissions by renewable energy resources, support measures for limiting the degradation of the environment and the climate – LATENERGI”.
3. The results of the thesis have been reported and have received positive evaluations at twelve international conferences:
   3.1. The 51st Annual International Scientific Conference of Riga Technical University, Latvia, Riga, October 14, 2010.
   3.2. The 6th International Conference on Electrical and Control Technologies ECT 2011, Lithuania, Kaunas, May 5 – 6, 2011.
   3.3. The 10th International Conference on Environment and Electrical Engineering EEEIC 2011, Italy, Rome, May 8 – 11, 2011.
   3.4. IEEE PES Trondheim PowerTech 2011, Norway, Trondheim, June 19 – 23, 2011.
   3.5. The 52nd Annual International Scientific Conference of Riga Technical University Power and Electrical Engineering, Latvia, Riga, October 14, 2011.
   3.6. The International Conference on Electrical Power and Energy Systems ICEPES 2012 (WASET), Switzerland, Zurich, January 15 – 17, 2012.
   3.7. The 7th International Conference on Electrical and Control Technologies ECT 2012, Lithuania, Kaunas, May 3 – 4, 2012.
   3.8. 9th International Conference on the European Energy Market EEM12, Italia, Florence, May 10 – 12, 2012.

3.9. Riga Technical University 53rd International Scientific Conference dedicated to the 150th anniversary and the 1st Congress of World Engineers and Riga Polytechnical Institute, Latvia, Riga, October 11, 2012.
3.10. The 12th International Conference on Environment and Electrical Engineering EEEIC 2013, Poland, Wroclaw, May 5 – 8, 2013.
3.11. IEEE PES Grenoble PowerTech 2013, France, Grenoble, June 16 – 20, 2013.
3.12. Riga Technical University 54th International Scientific Conference Power and Electrical Engineering, Latvia, Riga, October 14, 2013.

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1. In internationally quotable scientific journals:

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1.2. Berjozkina S., Sauhats A., Bargels V., Vanzovichs E. Detecting the Capacity Reserve in an Overhead Line// International Journal of Electrical, Electronic Science and Engineering. - 2012. - Vol.61. - pp. 327-332.
1.3. Berjozkina S., Sauhats A., Vanzovichs E. Simulations of the Allowable Load Current of the Overhead Lines in the Latvian Power Network// Journal of Energy and Power Engineering (JEPE). - 2012. - Vol.6. (No.9). - pp. 1521-1526.
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2. In internationally quotable collections of scientific articles:

2.1. Vanzovichs E., Aristovs T., Berjozkina S. Allowable Load Current Calculation Method with Heating Limitation for Overhead Powerlines// Abstract Book and Electronic Proceedings of the 51st Annual International Scientific Conference of Riga Technical University. - Riga, Latvia: RTU, 2010. - pp. 47-52.
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2.5. Berjozkina S., Bargels V., Sauhats A., Vanzovichs E. A Comparative Assessment of Conductors with Composite Core// Abstract Book and Electronic Proceedings of the 52nd Annual International Scientific Conference of Riga Technical University. - Riga, Latvia: RTU, 2011. - 6. p.

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STRUCTURE AND CONTENT OF THE DOCTORAL THESIS

The present thesis has been written in the Latvian language; it comprises an introduction, four chapters, conclusions and recommendations, a bibliography and twelve appendices. The total amount of the thesis is 170 pages in computer typesetting, which contains 65 figures and 14 tables as well as 12 pages of appendices. The bibliography lists 154 sources of literature.

1. FORMULATION OF THE HIGH-VOLTAGE POWER LINE OPTIMIZATION TASK, METHODS AND TOOLS TO BE USED

This chapter substantiates the importance of the role of high-voltage power lines in the power system both on a global and a national scale; it reviews the main structural elements of OHLs and the parameters that impact their mechanical, thermal and environmental restrictions, thus making it possible to find an optimum power line designing variant in close interaction. The topical directions of the new technologies are described, which are currently being developed, worked out, implemented, and modernized, adapting to the smart grid concept. The methods and approaches to be used in OHL design are reviewed, along with the mode control possibilities and algorithms; also, the possibility of using modern computer *software complexes is analyzed. Besides, the topical issue of the environmental impact of OHLs is addressed separately.*

1.1. The role of high-voltage power lines in power systems

One of the main elements of power systems is OHLs, the significance of which is steadily growing with the further development of the power industry. This is due to a number of reasons:

1) the generation of electricity takes place mainly in large power plants of various types, including thermal power plants (TPPs), hydropower plants (HPPs), nuclear power plants (NPPs), which are built in the vicinity of the required energy sources or in places where it is expedient from a technical or an economic point of view due to favourable territorial location, considering the local weather conditions;
2) the great impact of renewable energy sources (RES), especially wind and solar power plants, which are expected to dominate Europe's energy supply in a sustainable future energy system;
3) the need of an expansion of new electrical connections between countries due to the impact of important energy players such as the Russian Federation, which is expected to increase its generation capacities by the construction of a nuclear power plant (NPP) in Kaliningrad, as well as the NPP Visaginas (Lithuania) and Belarus with the capacity of 3000 MW and more, where the output and export of electric power of the new nuclear power stations to the Nordic countries will also require expansion of the internal power grid of the Baltic region, for example, between Latvia and Lithuania (Ignalina – Liksna, an existing 330 kV line) and between Estonia and Latvia (Sindi – Riga TPP-2, the 330 kV line under construction) [24];
4) the development of cross-border trade of energy.

As a result, an increase in electricity network expansion will be required both from a national and an international perspective. Thus, the increasing development of cross-border trade, using the mediation opportunities between the different national markets is stressing the existing cross-border backbones. As is known, significant PTN infrastructures in Europe as well in Latvia are undergoing wear, tear and obsolescence, creating „bottlenecks" in electric networks, which limit the transmission of energy. As a result, the throughput capacity of the existing OHLs becomes insufficient. The most recommendable solution in these cases would be to eliminate all the electric network "bottlenecks" and build new OHLs. Yet at present, the implementation of this solution is becoming increasingly difficult due to various limiting factors, for example, a complex regulatory framework, intensive use of land, visual impact, environmental issues, electromagnetic fields (EMF), public opposition, difficult terrain and weather, and, of course, commercial problems that lead to delay or even cancellation of many transmission expansion projects.

The above-mentioned topical aspects that affect PTNs in the world, are also attributable to the infrastructure of power networks in Latvia. It is known that the Latvian power system, like the power systems of the other Baltic countries, is operating in parallel with the power systems of Russia and Belarus in a joint ring network, the so-called BRELL network. The power supply to Latvia depends on the power plants of Latvia and the neighbouring countries operating in base mode; the operative reliability of their power systems largely depends on the operation of the BRELL ring network. In this way, the effective functioning of the power system requires infrastructure which can ensure the demanded electricity and heat generation capacities simultaneously with an equivalent power transmission networking that is adequate to the electric networks, as well as control of the system. Besides, the changes in the economy of Latvia and in the development of individual regions of the country create the need for both construction of new OHLs and substations and reconstruction of the existing PTLs and substations.

In order to successfully solve issues related to the ensurance of the energy balance and the regulation of power system modes, it is necessary to ensure a sufficient throughput capacity to the OHLs, thus enabling them to function as transport, intersystem, and system internal links.

1.2. The structures, parameters, restrictions and prices of high-voltage power lines

The principal structural elements of OHLs need to have a sufficiently high mechanical strength, therefore during OHL designing, mechanical calculations are also made along with electrical calculations, so as to determine not only the conductor type and cross-section depending on the installed transmitted capacity, but also the type of insulators and towers, the calculated span length, and the earth wire.

Like other engineering network infrastructure, OHLs are characterized by specific structural parameters, the principal ones of which are span length, conductor sag, ground clearance and clearance to crossed objects.

In order to find the best OHL designing alternative, it is compulsory that a number of restrictions be considered, for example, thermal (allowable conductor temperature and load current), mechanical (conductor sag, clearances), electrical (insulation level) and environmental (climatology, the impact of the electric and magnetic field (EF and MF)) [25].

There has not been a significant increase in new EHV lines over the recent years, although most grid owners have invested heavily in the reconstruction or modernization of the exisiting OHL with the purpose for increasing the capacity. The total 380/400 kV line length has increased by 3 percent (approximately 3,000 km) over the past 5 years; the OHL construction costs vary on a relatively wide range from 168200 to 401600 EUR/km [26].

1.3. The new technologies within PTL projects

In the development of the power transmission system, a key role is played by the utilisation of innovative technologies for transmission, with the goal of making the existing system “smarter”, i.e. more flexible and responsive to sudden changes of conditions, capable of handling large amounts of variable generation data as well as essentially to ensure an optimal and cost-effective PTN expansion. It can be achieved by a combination of direct technical reinforcements (new construction and ample use of improved hardware technology) to the PN itself along with indirect information and control reinforcements. In particular, it has become topical during the past decade, when advances in computer and communication technology have appeared, for example, SCADA (Supervisory Control and Data Acquisition) and EMS (Energy Management System), which have greatly improved data transmission capabilities providing access to relevant real-time data in order to be able to perform complex on-line analysis of PN. However, despite these improvements, various types of problems persist [27].

The study gives a brief review of the principal modern technologies; for example, it can be said that within the present study, the main interest is attracted to the review of high-temperature low-sag (HTLS) conductors and the prospects of their possible use, as well as real-time system monitoring devices, mainly OHL thermal load current monitoring systems.

1.4. OHL designing methods and tools

The essence of the task of designing OHLs and PTNs is the development of such solutions and technical and economic substantiations that determine their development at minimum capital investments and ensure standard-compliant supply of electricity to consumers, taking into account the existing technical restrictions. Conditionally, designing consists of three basic components (designing of PTLs, the PTL designing process and the PTL design as the end product), which continuously interact in time. In order to ensure effective action of the above group of main components, modern software complexes need to be used, for example, *PLS-CADD* [3] and *SAPR LEP* [4]. As a result, using such tools alongside the increasing of the designing speed makes it possible to optimize the adopted decisions for exact high-voltage power line designing conditions.

1.5. OHL optimization approaches

In the general case, in order to solve an exact statement of a power transmission task, various methods, approaches and structures are used, making up a set of alternatives; after that, a comparison is done and the best one of the proposed alternatives is chosen. The choice of the optimum alternative is based on a group of exact efficiency indicators and a corresponding technical and economic model, certainly complying with all the technical restrictions and the correspondence of the comparison conditions of the reviewed alternatives. As a result, it can be concluded that today's OHL optimization main task statement has to be complex, dynamic and multi-criterial, which is a complicated power-industry optimization task.

The mathematical model of the optimized task comprises three important bases: the target function, the restrictions and the limit conditions. Such a statement of the task can be interpreted in Fig. 1.1, where it is clearly seen that the existing restrictions (mainly technical, economic, environmental ones, with political restrictions as an additional impacting factor) limit the allowable area of the choice of the optimum solution. As can be seen on Fig. 1.1, investments form the economic substantiation of the choice of the OHL design optimization task at the condition of present-day competing markets of the power industries.

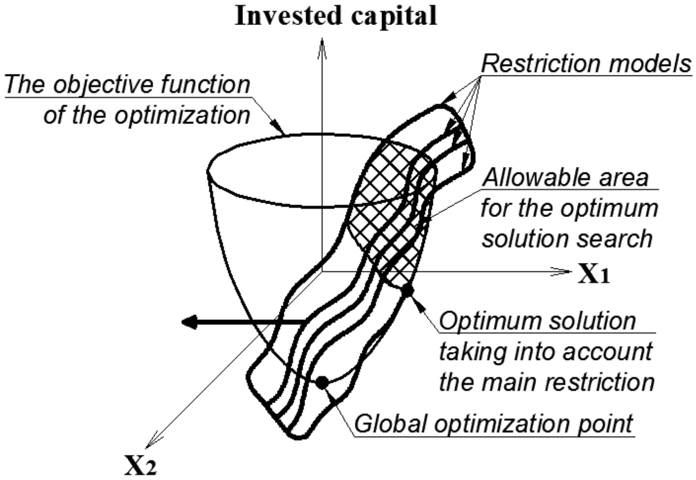


Fig. 1.1. The graphical illustration of the OHL optimization target function

1.6. The methods for evaluating an investment project

The most widely used methods in OHL designing are those based on cost and revenue analysis and increasing of the NPV or diminishing the capital costs, taking into account a number of restrictions.

In the designing of power facilities, including OHLs, the most widely used investment project evaluation methods are the following [5]: the net present value (NPV) method, profitability index (PI) of the project, the internal rate of return (IRR) , the modified internal rate of return (MIRR), the project payback period.

The present thesis postulates the statements of the task for economic substantiation, which is based on a real-life design example – the ”Kurzeme Ring” (action 1), which comprises the construction of 330/110 kV OHLs; the NPV method will be used, which takes into account the change of investment value over time and is one of the most frequently used and the most appropriate methods for evaluating the economic efficiency of any investment projects in the power industry (see Subchapter 4.3).

1.7. The possibilities of controlling OHL modes and the appropriate algorithms

The throughput capacity of the existing PN deteriorates over time – the degree of ramification of the network increases and its configuration becomes more complicated (the transferred power is limited by the criterion (n-1)), which is currently causing one of the topical problems of network power industry, namely, the insufficiency of the throughput capacity of the existing OHLs. In the cases when an emergency trip is superimposed to a repair scheme, redistribution of power flows may result, and does result, in an inadmissible increase in the loading of individual elements of power networks and their overload.

In order to eliminate inadmissible overload of PN elements, among them OHLs, the following possibilities for controlling the modes of OHLs are foreseen:

1) regulation of generating capacities and OHL capacity distribution modes;
2) regulation of the load of the consumers;
3) use of flexible alternating current transmission systems – FACTS;
4) use of new automation devices based on microprocessor elements and introduction of OHL monitoring systems.

1.8. The environmental impact of high-voltage power lines

An OHL as an element of an electric power system has a direct contact and interaction with the environment. In the designing and construction of OHLs, the most characteristic environmental problems to be faced are land alienation and confiscation, which impacts agriculture; cutting of trees in forested areas; restriction of agricultural activity in the OHL alienated area, thus threatening the integrity of fields and pastures; impact of EF and MF; emergence of television and radio interference; acoustic noise; deterioration in the operation of means of communication; deterioration of the aesthetic perception of the landscape in the locations of the OHL route. Part of the above environmental impacts are quantifiable and can be expressed in the form of economic indicators. Yet the most impacts onto the biosphere and the social systems are complicated and sometimes even impossible to evaluate. As can be seen, it can be concluded that the environmental impact of OHLs is extremely multifaceted, yet the main specific factors affecting the environment to be mentioned are EF and MF, acoustic noise as well as the aesthetic impact of OHLs [28].

2. THE MATHEMATICAL FORMULATION OF THE HIGH-VOLTAGE POWER LINE OPTIMIZATION TASK

This chapter looks at the formulation of the OHL multicriterial optimization task and the statement of the principal approach task. The target functions and restrictions have been formulated and a definition of the scenario approach and Pareto’s approach is given. An algorithm and a method for solving the high-voltage line optimization task has been given.

Besides, the theoretical basis of the synthesized OHL capital investment distribution method is reviewed, which relies on the approaches of coalition founding and Shapley's distribution.

2.1. The statement of the principal approach task

The research of this thesis deals with an OHL design method which is also partially based on the stochastic approach and game theory criteria to be applied for making the final decision for the real-life implementation of energy facilities [29]. For this purpose, the following five steps are taken:

1. Based on an analysis of the development plans of a region, scenarios implying a rise in the load are developed, and the corrections to be introduced into the requirements for the OHL transmission capacities are estimated.
2. Using the relevant software with an appropriate database, a number of competitive structural variants and OHL parameters are selected. The most impacting restriction is defined.
3. Evaluation of the capital costs and expected NPV of all the variants – both when the restrictions are observed and in the case when one of them is violated.
4. The whole variety of the competitive decisions is constructed. The plane of capital costs and the parameter that characterizes the restriction are used.
5. Assessment is performed for the probability of the conditions that allow for restriction removal, its consequences and the relevant preventive measures.

2.2. The probabilistic and uncertain parameters and their influence

In order to formulate the tasks of OHL designing with account of the influence of random and uncertain factors, we will make the following assumptions [29]:

- The company which is the owner of OHL strives to minimize the invested capital I_C and increase its revenues R_{ti} (the net cash flow, i.e. the cash inflow/ outflow, for each year t_i of the planning period $T=m \cdot t_i$).
- Revenues R_{ti} and invested capital I_C of the company depend on the multi- structure Σ_j and parameters Π_j of the OHL chosen by this company. The structures Σ_j are described as those of discrete variables (the number of wires per phase, the height and parameters of standard towers, the cross-section of the conductor, its mechanical and electrical parameters, etc.). Each structure of the type presents alternative A_j (j=1, …, N). The parameters Π_j are described by a set of continuous variables (the span lengths, the coordinates for the construction of towers, etc.).
- The freedom of the company in choosing the structures and parameters is limited.
- S_j is the set of all permissible structures and parameters for the OHL and $s_j = \{\Sigma_j , \Pi_j\}$ is the chosen combination of the structure and parameters, s_j э S_j. The frontier confining the space of the permissible structures is determined by inequations that describe the technical and legislative factors and regulations.
- OHL functions under the influence of ambient environment are characterized by a set of random and uncertain parameters X_{ti} (load current in a power line, ambient temperature, wind speed, humidity, etc.). In the general case, parameters X_{ti} vary with time. In our case, these parameters are assumed to be constant for each year t_i.

2.3. Target functions and restrictions

Due to the influence of random and uncertain factors, the revenues are also uncertain: in this case, the approach involving different scenarios in combination with probabilistic variables can be used for solving the task of planning. The uncertain information will always be modelled by a number of scenarios. For each scenario SC_n (n=1, …, k), we can state that revenues R_{tij} are probabilistic values, i.e. [29]:

$$R_{tijn} = R_{tijn}\left(s_j, X_{tijn}\right) \tag{2.1}$$

Suppose that the following distribution functions:

$$F_{tijn} = F_{tijn}(R_{tijn}\left(s_j, X_{tijn}\right)\middle| SC_n, A_j). \tag{2.2}$$

may be assigned to each combination of scenario SC_n and alternative A_j.

If the distribution function is known, the expected value of a year's t_i revenues for each SC_n and A_j combination can be determined by the equation with the Lebesgue-Stieltjes' integral [30]:

$$E\left[R(s,\mathrm{X})\right] = \underset{\Omega}{\int \ldots \int} R(s,\mathrm{X})dF(R(s,\mathrm{X})), \tag{2.3}$$

where Ω is the integration area limited by the space of random parameters X. The frontier of the space for allowable parameters and structures S_j is determined by the following inequation:

$$FR\left(s_j, X_{ti}\right) > 0. \tag{2.4}$$

Knowing the expected revenue values, we can derive the equation for determining the net present value as the main optimization criterion:

$$NPV = -I_C + \sum_{i=1}^{m} \frac{E(R)}{(1+I)t_i}, \tag{2.5}$$

where I_C is the investment capital, which is a function of s_j.

The optimum planning task can thus be presented as:

$$s^*_{jn} = \arg\max\left(-I_C + \sum_{i=1}^{m} \frac{E(R)}{(1+I)t_i}\right), \tag{2.6}$$

where arg is "the argument for" the subject of maximization; I is the discount rate.

Solving Eq. (2.6) will yield the system's structures and parameters s^*_{jn} that maximize NPV for the planning period T for all selected scenarios SC_n and alternatives A_j. For each SC_n-A_j combination the NPV estimate can be found. In the NPV maximization process, an extended space s^*_{jn} is added in order to determine the alternatives and parameters approaching the frontier of the allowable space that can be stored beyond its limits. These parameters (R_i) will be reviewed as additional criteria in the optimization. Having obtained the NPV and R_i values for all combinations of scenarios and alternatives, we can formulate the relevant matrix (see Table 2.1). After that, it remains to choose the best alternative. In the given set of alternatives there are even solutions that lead to removal of the most impacting restrictions.

Each of the columns in Table 2.1 may contain a Pareto's set; if there are constraining indices R_i, consider the second optimization criterion (note that in the general case such indices can be numerous).

Table 2.1

The expected NPV values and restriction indices Rr_i

Alternatives	Scenario 1	…	Scenario k
A_1	NPV_{11}‖ Pr_{11}	…	NPV_{1k}‖ Pr_{1k}
…….	…….	…	…….
A_N	NPV_{N1}‖ Pr_{N1}	…	NPV_{Nn}‖ P_{Nk}

In the search for the best OHL alternatives, we should take into account several restrictions: thermal, mechanical, electrical and environmental [24]. In designing an OHL, it is necessary to estimate the adjusted maximum load current, the ground clearance as well as the clearance to the crossed objects, and the distributions of EF and MF. Since a large number of optimization parameters are discrete, it can be argued that for solving the optimization task formulated in Eq. (2.6) it is necessary to perform the investment calculations for all possible combinations of parameters s_j corresponding to the area that meets $s_j \ni S_j$ restrictions. Generally, if one of the restrictions is not met, the alternative is not taken into account in the optimization task and is rejected. However, in this study those alternatives are considered in which such restrictions are removed: for this, new technical possibilities (e.g. Smart Grid), different monitoring systems as well as the high-temperature low-sag (HTLS) conductors could be applied. Thus, the proposed approach allows some restrictions to be removed (with the relevant probability estimation).

2.4. The scenario approach and Pareto's approach

The need for the construction of a new OHL is substantiated based on the forecasts of economic development for a certain geographic region, mainly this applies to new expected loads or an increase in the existing loads; new generation sources; failure to provide reliable and high-quality electricity demand through the existing PNs. Under uncertainties, various scenarios should be considered – e.g. concerning the load increase. After the power system development scenarios have been selected, different alternatives are examined with the purpose of choosing the optimization parameters S_j (see Subchapter 2.3).

The following parameters can be the subject of optimization: the nominal voltage of OHL; the mechanical and electrical characteristics of the conductor (its diameter, cross-section, the coefficient of linear expansion, the modulus of elasticity, the allowable temperature and the load current; specific, linear and destructive loads); the type of conductors and their number per phase; the type of tower, its geometry, height, the allowable wind, weight and clearance spans; the type of insulators and dampers; the lightning wire type and optical ground wire (OPGW) type; the earthing and lightning protection systems; the optimum line route. Thus, to achieve the best technical and economical solution of the OHL design, a large number of optimization variables should be taken into account. As mentioned previously, any OHL is under the influence of ambient environment (described by set X_{ti} of random and uncertain parameters).

The task of estimating the revenues at a large number of scenarios and alternatives (combinations included), choosing among numerous optimization variables, is therefore very complicated. To simplify it, another task – that of filtering less competitive variants – is formulated and solved by disregarding obviously expensive or unreliable ones. Until recently, this task was solved based on experience, with various guidance documents issued. In the last decades, powerful software tools are used [3, 4], which give the opportunity to form a significantly smaller initial set of competitive alternatives. Then estimation should be performed for the effectiveness and appropriateness of each alternative in each scenario with account of the technical and legislative restrictions.

Additional reduction of the number of the competitive variants may be achieved by using a simplified optimization task form. In this case, the task is formulated as follows:

$$S_{ij} \approx \arg\min I_C, \tag{2.7}$$

The equation (2.7) is much easier to use than (2.6). Using the simplified formulation of the problem, the obviously non-competitive variants of a project are discarded. Note that the considered problem (2.7) does not take into account a number of important factors (for example, the power losses in a line) and it can be implemented only for reducing the number of the options, which are subject to further consideration with the use of (2.6).

In the present thesis, the plane of Pareto's set of solutions has been constructed on the basis of two contradicting criteria, investments and EF intensity, enabling the adoption of the final decision for solving an exact task – to choose the most efficient (the most profitable) OHL designing investment project (see Subchapter 4.3) [29].

2.5. The algorithm and method for solving the optimization task

The construction of a new PTL has the following main purposes: it interconnects new generation and resource areas within the network (there is integration of renewable, fossil, hydro and nuclear resources); improves the reliability of the grid (there are economic and congestion reasons) as well as manages risk of non-delivery of power by providing access to additional generation resources; increases the efficiency of OHL operation due to reduction of line power losses; makes wholesale markets more competitive and efficient; reduces the network load by forming new transmission power nodes and paths [31]. Taking into account the importance of the above-said, the algorithm for solving the optimization task can be presented as a block scheme (see Fig. 2.1).

The NPV calculation is a difficult and very time-consuming task. There are difficulties that are determined by the following main factors:

- The price of OHL elements needs to be taken into account, which will be defined "experimentally" by conducting negotiations with the stakeholders (the compensation of the land value for the OHL route; the cost of the conductors, towers and line fittings, the conditions for getting a credit etc.)
- There is a lack of a common recognized methodology of revenue, which occurs as a result of calculating the OHL construction expenses calculation.

In this study, let us accept the following hypotheses:

- The OHL construction is determined by the necessity of grid development for providing the planned consumption growth and energy transit;
- The construction projects are realized by a coalition, which consist of two companies – C_1, the owner of the existing network, and C_2, the owner of new facilities, in particular a new power line;
- The construction of the new OHL provides receiving the additional annual revenue of the transmission grid, which is equivalent to the normalized percentage (generally, 7-12 % [26]) of the average cost of energy transit;
- The division of total additional revenue (R_{ad}) and additional revenue of each company (R_{C1}) and (R_{C2}) is based on Shapley distribution, which in case of two players is elementarily simple [32]:

$$R_{C1} = R_{C2} = \frac{R_{ad}}{2} \tag{2.8}$$

In this study, suppose that the additional income of the PTN is distributed among the existing network and newly built objects in an equivalent proportion, and then we obtain the amount of annual income:

$$R_{inc} = \left(\frac{I_l}{I_s}\right)\frac{R_{ad}}{2}, \tag{2.9}$$

$$\text{where } R_{ad} = \beta(E_{an}+E_{antr}), \tag{2.10}$$

where I_S – annual investment in a PTN; I_l – investment in the OHL construction; E_{an} – annual growth of power consumption; E_{antr} – transit energy growth; β – rate of the energy cost.

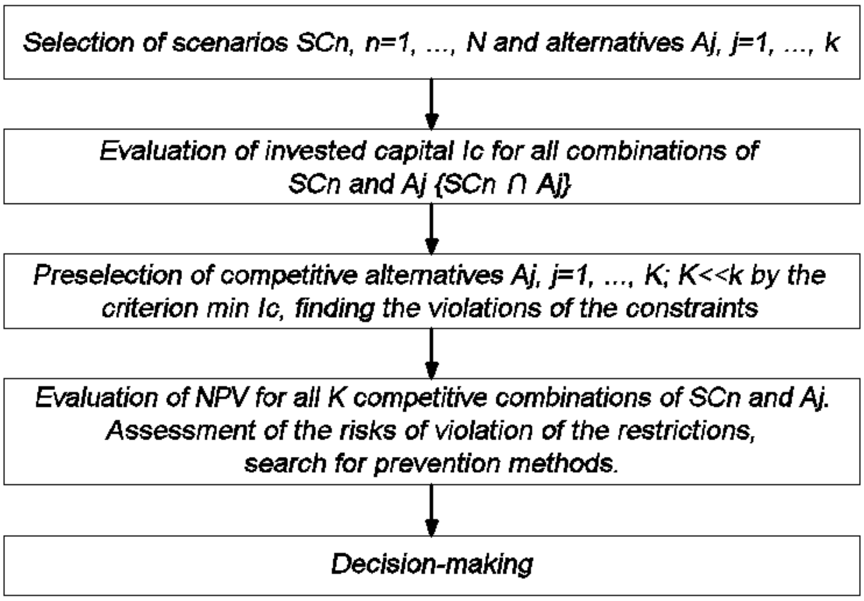


Fig. 2.1. The block scheme of the algorithm for solving an optimization task

2.6. Founding of coalitions and Shapley's distribution

The present paper will be considering the second case, when an additional condition is assumed that competing enterprises can form coalitions with the main aim of gaining additional revenue.

Let us imagine the task of power supply development planning in the form of a static game with complete information [33]. The game is presented in normal form as follows:

$$\left\{I, S = \prod_i \{S_i\}\, i \in I, R = \{R_1, R_2 ... R_n\}\right\} \qquad (2.11)$$

where I is a list of players, $\left\{S = \prod_i \{S_i\}\right\} i \in I$ is all situation combinations and revenues R are of each player at all his strategies and at each combination of the competitors' strategies.

It is assumed that the list and number of the players (company) is known; also, that each player knows the revenues at any combination of structures and parameters of all the players. It is necessary to solve the following problems:

- ✓ Determining the rationality and possibility of organizing a coalition among the players.
- ✓ Choosing the methods for organizing the coalition and distributing additional revenues among the participants of the coalition.

If the possibility to form a coalition is taken into account, the formulation of the optimization task is modified once more. Due to the need to consider not only the strategies of individual companies, but also those of possible coalitions in various combinations, the dimension of the task increases considerably. Resulting from the solution of this task, the set of the sub-optimum plans for each company and their coalitions at various combinations of the possible competitors' plans can be obtained.

In case of cooperative behavior, there is a problem of revenue distribution between the members of the coalitions. The simple approach would be to give each player his contribution c_i:

$$c_i = R\left(S \cup \{i\}\right) - R(S). \qquad (2.12)$$

where R(S) is the revenue of the coalition S, $R(S \cup \{i\})$ is the revenue of the coalition S with the participation of the actor i. However, such an approach is not anonymous, i.e. ordering of the players makes a difference in the amount they are rewarded.

In game theory, a Shapley value [33, 34] describes one approach for the fair allocation of gains avoiding the mentioned drawback. Fair allocation is ensured by uniformly selecting a random ordering and rewarding each player with the expected marginal cost according to the ordering. Since players can form n! possible random orderings, the probability of set S being ranked exactly before player i is: $\frac{|S|!(n-1-|S|)!}{n!}$. Thus the additional amount that the player i gets is [12]:

$$\phi_i = \sum_{i \notin S \subseteq N} \frac{|S|!(n-1-|S|)!}{n!} \big(R(S \cup \{i\}) - R(S) \big), \qquad (2.13)$$

Where n is the total number of players, |S| is size of the set S, the sum extends over all subsets S of N not containing player i.

In the simplest case, when only two players participate in the game, the expression (2.13) is simplified and acquires the following form [12]:

$$\phi_1 = \phi_2 = \frac{\big(R(S \cup \{i\}) - R(S) \big)}{2}. \qquad (2.14)$$

This means that in this case, the additional revenue is divided in half.

3. RESTRICTION MODELS, THEIR VERIFICATION AND CONTROL

The present section is dedicated to the results of the experimental measurements of the main OHL parameters for various existing high-voltage lines in Latvia at a number of operating modes at local weather conditions. Based on an analysis of the results obtained by the verification models of the OHL allowable load current monitoring system (from the thermal point of view), a synthesized OHL allowable load current monitoring algorithm was proposed, using which allows improving the accuracy of estimating the allowable conductor temperature and load current for existing OHLs or OHLs under design and makes it possible to adapt to dynamically operative OHL control and monitoring in real-time mode.

3.1. Experimental testing of OHL parameters

For the verification of the OHL allowable load current monitoring algorithm synthesized within the present thesis, experimental measurements of the main OHL parameters – conductor temperature, ambient temperature, wind speed and wind direction as well as air humidity – were carried out, by using a simplified set of OHL parameter measurement devices (special monitoring equipment), which can be seen in Fig. 3.1:

a) The conductor temperature was measured using special thermovision equipment, for example, *FLIR ThermaCAM P65* (see Fig. 3.1. a)) [1];
b) The clearance was measured using a cable height meter (see Fig. 3.1. (b));
c) The ambient temperature and humidity was measured utilizing a thermohygrometer, for example, *Testo 635-1* (see Fig. 3.1. (c));
d) The experimental measurements of wind speed and direction were conducted by using a pocket weather tracker, for example, *Kestrel 4000* (see Fig. 3.1 (d)).

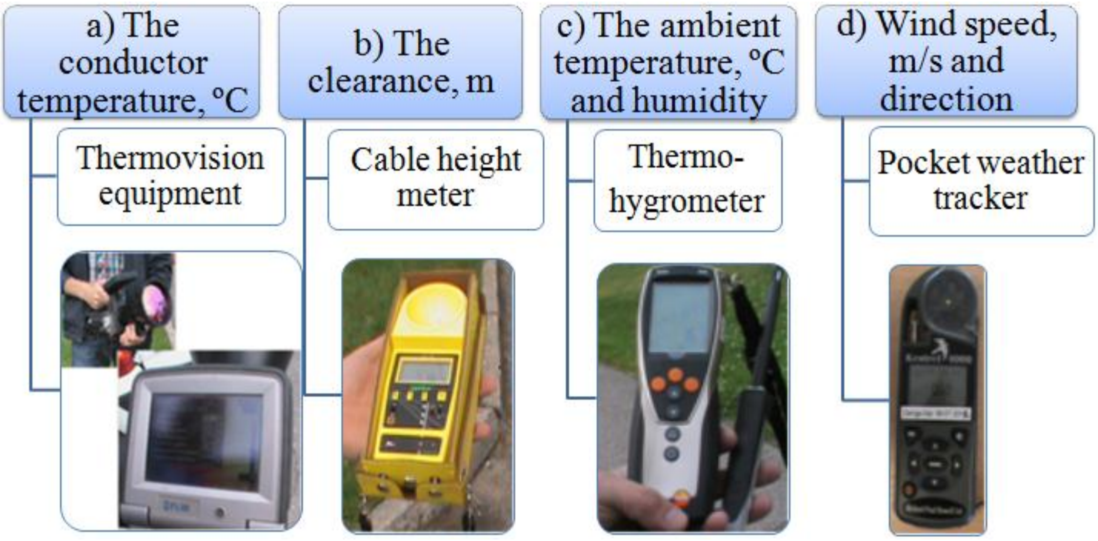
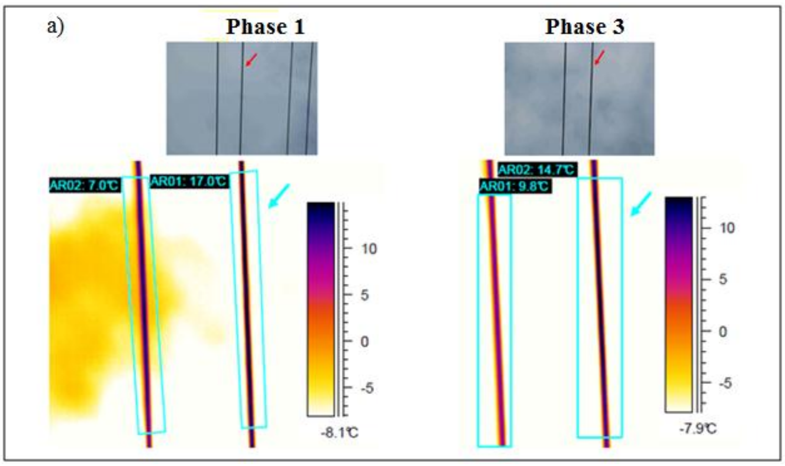


Fig. 3.1. The applied monitoring equipment

3.2. The measurement results for the principal parameters of existing OHLs

As was mentioned before, one of the main OHL allowable load current monitoring system parameters is conductor temperature. Therefore, a number of conductor temperature measurements were conducted at the local weather conditions for the following existing OHLs of the Latvian power system at specific spans: Line No. 600 – for the span between towers No. 1 and 2; Line No. 501 – for the span between towers No. 53 and 54; Line No. 321 – for the span between towers No. 17 and No. 18; Line No. 303 – for the span between towers No. 59 and No. 60. For example, the results of experimental measurements of weather conditions (ambient temperature, air humidity, wind speed and direction), thermal (conductor temperatures) as well as electrical (load current, voltage) are reflected both in graphical form (see Fig. 3.2.) and in table form (see Table 3.1.). It is useful to note that the conductor temperatures in the phases are lower as compared with ambient temperatures, which is not precise, yet this is permissible, since the error of the conductor temperature metering device is within the permissible boundaries, i.e. ± 2°C (see Tabel 3.1.). Therefore, with every considered OHL case, the highest measured phase conductor temperature is taken as the initial parameter for verifying the thermal load current estimation methods (see Subchapter 3.3).



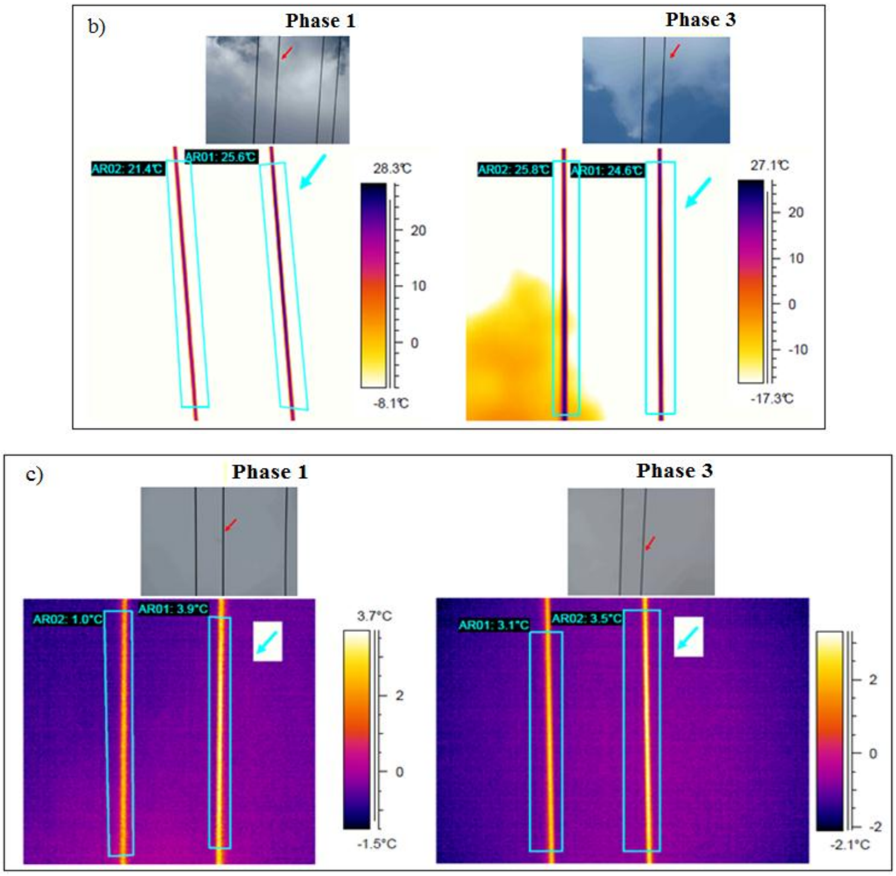


Fig. 3.2. The experimental results of OHL No. 600 for the span between towers No. 1 No. 2 for: case A for phase 1 and 3 (a); case B for phase 1 and 3 (b); case C for phase 1 and 3 (c)

Table 3.1

OHL No. 600 measurement results

Parameters / Obtained measurement data	Case A	Case B	Case C
	Towers No. 1 – No. 2		
Voltage, kV	115	115	117
Load current, A	37	162	73
Active power of load, MW	2	31	7
Reactive power of load, MVar	7	9	13
Conductor temperature of phase 1 (AR01), °C	17	25.6	3.9
Conductor temperature of phase 2 (AR01), °C	-	-	-
Conductor temperature of phase 3 (AR01), °C	14.7	25.8	3.5
Ambient temperature (ta), °C	17	21	3
Wind speed, m/s	2-5	1-2	3-5
Wind direction	western	western	southern
Weather conditions	partly cloudy	sunny	cloudy
Conductor type	2xAS-240/32		
Allowable load current at ambient temperature: + 20°C	1271 A	1271 A	
+ 5°C			1452 A
Line loading, %	3	13	5

3.3. Verification results of the OHL allowable load current monitoring system models

There are two general possibilities for monitoring conductor temperature [35, 36]:

I. Direct monitoring entails the direct measurement of conductor temperature, which is, however, inconvenient for the operation of a line;

II. Indirect monitoring entails thermal rating calculation methods, which use the measurements of the key parameters that impact the allowable conductor temperature.

In this subchapter, we will look at two main verification models of the OHL allowable load current monitoring system (from the thermal point of view), analyzing the results obtained by solving existing problems from various standpoints:

1. Direct monitoring by using measurements of principal parameters, for example, conductor temperature, ambient temperature, air humidity, wind speed and direction;
2. Indirect monitoring by using the calculated values of the above principal parameters.

- <u>Verification models of the OHL allowable load current monitoring system, using measurement results</u>

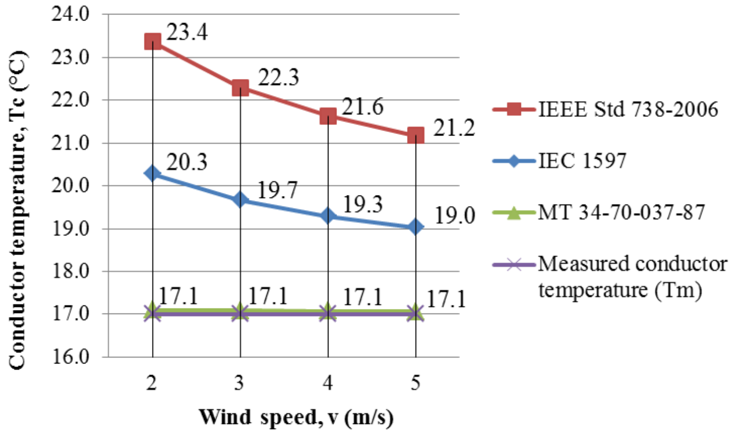
Implementation of a model of thermal rating methods evaluation was performed in three main steps in this study:

1. An exisitng OHL has been selected, the initial parameters of an exisitng line need to be determined – the physical, mechanical and electrical characteristics;
2. All the necessary weather parameters under the chosen circumstances have to be measured or assumed according to the local conditions, for example, in this case, the ambient temperature, wind speed and direction as well as the air humidity were measured by using special equipment;
3. Evaluation of thermal rating methods (IEEE Std 786-2006 [37], IEC 1597 [38] and MT 34-70-037-87 [39]) based on the analysis of obtained values of the measured and calculated OHL conductor temperatures and sags at detected weather conditions was done. The mathematic equations of the above-mentioned methodologies were used for computing the parameters.

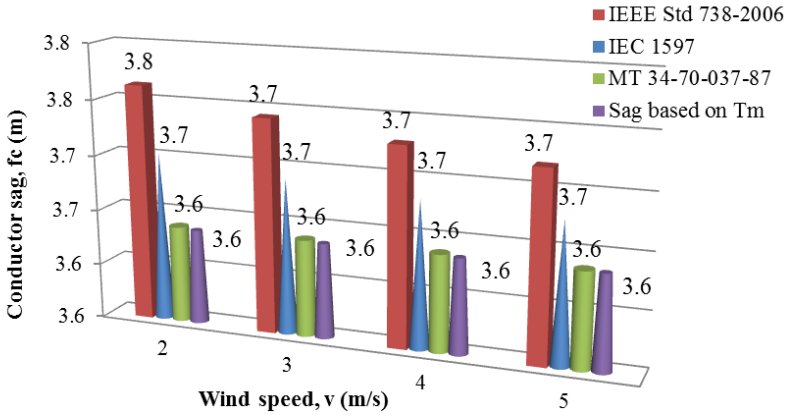
For example [36], study case A for OHL No. 600 presents a comparison of steady-state conductor temperatures both measured and calculated at several wind speeds in Fig. 3.3. a). Here the measured conductor temperature (Tm), which is 17°C (the highest conductor temperature for phase 1 has been assumed), is compared with the estimated conductor temperatures (Tc), which are defined according to the particular thermal rating method. Analyzing the results, the diagram shows that the largest difference in the measured and calculated conductor temperature values is observed when using the IEEE Std 738-2006 method (Tc = 23.4°C), then there is the IEC1597 approach (Tc = 20.3°C), which has a lower difference percentage, and the last one is the MT 34-70-037-87 method (Tc = 17.1°C) at a wind speed of 2 m/s (the worst case). It is worth noting that Tc, which is 17.1°C at all wind speeds by using the thermal rating method MT 34-70-037-87, has almost identical values as the measured conductor temperature (Tm is 17°C), thus it can be concluded that such a method is quite accurate.

Not only the conductor temperature (the thermal limitation) can be one of the general criteria in the evaluation of thermal rating methods, but also the conductor sag (the mechanical limitation) is a key impacting parameter by which the ground clearance as well as the clearance to the crossed objects is determined. Analyzing the obtained results, it can be seen that the maximum conductor sag – up to 3.8 m – is observed in case of using the IEEE Std 738-2006 method due to higher calculated conductor temperatures (see Fig. 3.3 a)); by contrast, the smallest conductor sag, 3.6 m, is observed when the MT 34-70-037-87 thermal rating approach is used (see Fig. 3.3. b)). It is obvious that a difference in the conductor sag values is present; the maximum difference is up to 20 cm. It is important to note that for Case A, the current obtained in the measurements (Im) is 37 A, therefore the OHL loading in the actual real-life example (see Table 3.1) is only 3%, but if the OHL loading were higher (for example, Case B), the conductor sag would also increase accordingly (for Case B, the conductor sag increased by 30 cm [35]).

The remaining analysis of the OHL calculation example thermal load current evaluation concept can be found in [25, 35, 36, 40].



a)



b)

Fig. 3.3. The obtained results based on the existing line No. 600 experimental data for case A: a) steady-state conductor temperature; b) conductor sag

- <u>Verification models of the OHL allowable load current monitoring system, using calculation results</u>

This study deals with the impact of the thermal and mechanical limitations in the load current of an existing overhead line with the purpose of finding the hidden capacity in the examined power line by using the theoretical background of the most appropriate MT 34-70-037-87 method and based on the particular OHL computation example (OHL No. 309) in accordance with its basic requirments. That is, the impact of conductor temperature on the allowable load current of the conductor will be considered, taking into account the standard ground clearance and the weather conditions. In this case, maximum conductor temperature is assumed as an already known value, thus, based on this condition, the permissible load current is calculated.

In this research, the conductor was evaluated at four different conditions – A, B, C and D, which are based on the heat balance equation concept, considering two basic cases: before and after the reconstruction of the OHL under discussion [41].

Analyzing the obtained results, it can be concluded that for both variants, the permissible conductor temperature has a rise tendency as the conductor temperature increases. Moreover, the permissible conductor temperature ranges from 50°C to 88°C, which means that 70°C (the temperature that is laid down in the Standard [23]) is not the thermal limit for the examined OHL (see Fig. 3.4). Besides, the first variant, which is the worst, is characterized by smaller permissible conductor temperature values than the second variant, which is to be considered favourable because of larger ground clearance. As a result, the impact of the mechanical limitation (conductor sag) is less in the second case.

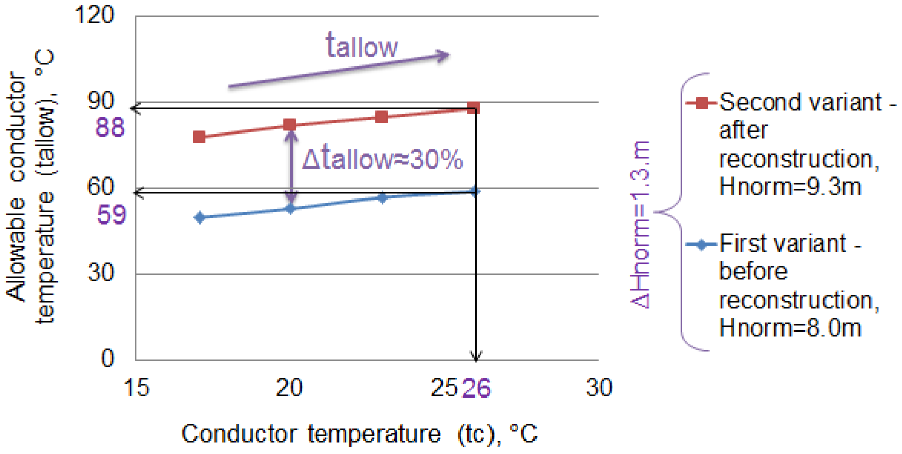


Fig. 3.4. OHL No. 309 dependence of the allowable conductor temperature on the thermal limitation (conductor temperature) and the mechanical limitation (OHL ground clearance)

Once the permissible conductor temperature has been determined, the next step is to define the capacity reserve, which includes the difference between the two examined variants; in this case, it is the mechanical limitation – the OHL ground clearance. The results of the first variant are presented in Fig. 3.5. a), which shows the dependence of the maximum load current on the thermal limitation – conductor temperature, permissible conductor temperature, the mechanical limitation and the weather conditions. The results of the second variant are presented in Fig. 3.5. b), which, similarly to the first variant, shows the dependence of the maximum load current on the above-mentioned, both the thermal and mechanical limitations and the weather conditions, but with a higher ground clearance – 1.3 m. This clearance reserve allows increasing the maximum load current of the overhead line, taking into account the thermal limitation and certain climate conditions. Indeed, the capacity reserve of the power line has increased, as has the ground clearance. For example, in the first variant, if it is assumed that the conductor temperature is 26°C, the wind speed is 2 m/s and the ambient temperature is 17°C (we are considering Variant D), the maximum current is 1707 A (see Figure 3.5 (a)), whereas in the second variant, after the reconstruction, at the same conditions, the current increases up to 2215 A (see Figure 3.5 (b)). Analysing the difference between maximum current values, it can be concluded that the second alternative states the existence of a thermal load current reserve in a certain OHL, which is based on four checked conditions and several sets of weather conditions, which makes it possible to utilize by 30% more of thermal load current without deterioration of the electrical parameters of the observed OHL.

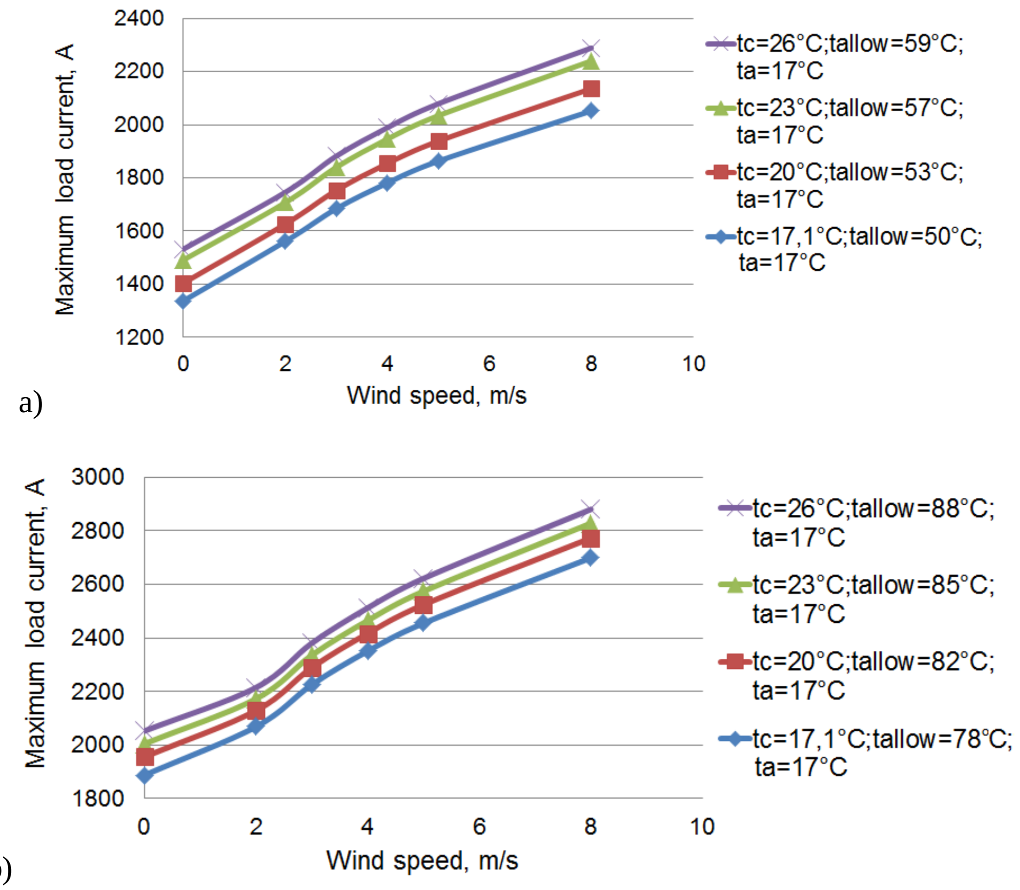


Fig. 3.5. Maximum load current of a conductor of OHL No. 309, based on the main conditions: a) first variant; b) second variant

The obtained calculation results for permissible conductor temperature and maximum load current, which rely on the theoretical basis of the method MT 34-70-037-87, help to evaluate the potential additional clearance, make it possible to reveal the hidden thermal load current reserve and improve the accuracy of determining the maximum load current, taking into account both the thermal restrictions and the mechanical ones as well as the weather conditions on the basis of a calculation example for an existing OHL. As a result, the gap or additional reserve was determined in the increase of the ground clearance, which allows finding additional throughput capacity for existing PTLs or transmission lines under design.

The remaining analysis of the OHL calculation example thermal load current evaluation concept can be found in [21, 41, 42, 43].

3.4. The possibilities for controlling the operating modes and replacing the conductors of existing OHLs

The main task, both when building a new OHL and operating the existing one, is the reduction of costs in power transmission, which can be achieved, for example, by monitoring the permissible limits of OHL conductor temperatures, load currents or sags as well as using high-temperature composite core conductors of a new design (with the possibility of retaining the existing towers).

One of complex solutions for operative monitoring of the current state of OHLs and optimization of the utilization of their actual throughput capacity is a system for monitoring OHL allowable load current. Introduction of the new monitoring system will make it possible to trace the condition of OHLs pratically in on-line mode and, consequently, find their actual throughput capacity, which will make it possible to promptly use the ”additional” or ”reserve” throughput capacity of OHLs without exceeding the permissible conductor temperature, for example, in emergency and post-emergency modes. Such a solution is an optimum one, if it is necessary to increase the throughput capacity of an existing OHL, since it allows retaining the existing conductors, not interrupting the operation of the OHL.

With this in mind, in order to develop the synthesized OHL allowable load current monitoring algorithm (from thermal point of view), experimental testing of the principal OHL parameters was carried out (see Subchapters 3.1 and 3.2), verification analysis of the OHL allowable load current monitoring system (from thermal point of view) has been provided for a number of models, based on the results of both measurements and calculations (see Subchapters 3.3), thus evaluating the validation of the theoretical basis of thermal load current estimation methods. As a result, the method MT 34-70-037-87 was selected as the main basis of the synthesized OHL allowable load current monitoring algorithm, which is reflected in Fig. 3.6, where kur T_C – conductor temperature, T_{Cp} – permissible conductor temperature, F_C – conductor sag, F_{Cp} – permissible conductor sag, C_C – ground clearance or clearance to the crossed objects, C_{Cp} – permissible ground clearance or clearance to the crossed objects, H – calculated MF distribution, H_p – permissible MF distribution, E – calculated EF distribution, E_p – permissible EF distribution [36].

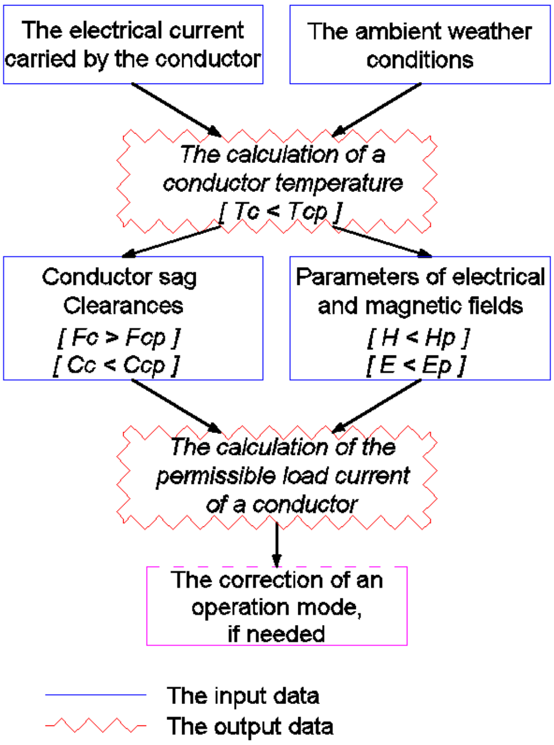


Fig. 3.6. The concept of the synthesized OHL allowable load current monitoring algorithm

The operation process of the given synthesized OHL allowable load current algorithm can be presented in four main stages (see Fig. 3.6):

I. When we know the electrical current carried by the conductor and the ambient conditions, then we can calculate or measure the conductor temperature; of course, it may not exceed the permissible conductor temperature value adjusted by the physical characteristics of the conductor (the technical documentation of the conductor manufacturer needs to be considered);

II. When the conductor temperature is found, it is necessary to estimate the conductor sag and the ground clearances or clearances to crossed objects as well as the parameters of EF and MF, which must be in the area of allowable standard values;
III. The next step is to determine the permissible load current of the examined conductor, taking into account all the previously computed parameters.
IV. Finally, correction of the OHL operation mode can be performed, if it should be necessary.

Besides, there is a possibility to replace the ACSR type conductors of the existing OHLs with HTLS conductors of new designs, since the majority of all the existing ACSR type conductors that are currently in operation, are outworn and obsolete as a result of a long service life. This means that in the cases when it is necessary to improve the throughput capacity of an existing OHL or to improve the deficient size of OHLs, it may be an efficient optimum solution with minimum costs (the reconstruction of an existing OHL requires less investment than the construction of a new OHL) since optimized high-termpature conductors have such advantages as a high throughput capacity, long-term reliability, lower sags under load, quick and simple installation, and low power losses. Recently, this high-voltage power line optimization method has been one of the most discussed problems in the modernization of contemporary power systems. In order to be able to make a more detailed evaluation of composite core conductors and their utilization possibilities, a number of technical and economic comparisons with ACSR type conductors were made, based both on the ”Kurzeme Ring” project (action 1), which comprises 330/110 kV OHLs, and on examples of existing OHLs (see Subchapter 4.2).

4. OHL DESIGNING EXAMPLES AND RESULTS

This section looks at OHL optimization examples and the results of their examination – the use of the OHL designing method that is partly based on the criteria of the stochastic approach and the game theory for adopting the final decision regarding the implementation of PTLs; also, the optimization of OHLs with an example of founding a coalition. Additionally, the section addresses the topical issue related to the integration of new technologies – high-temperature conductors with composite core, as a result giving a substantiation of the rationality of such an optimization solution. The above-mentioned research results are both based on a significant real-life power infrastructure facility within the Latvian and Baltic power systems, the Kurzeme Ring project (action 1), comprises 330/110 kV OHLs, *and the existing OHL calculation models, applying state-of-the-art software complexes, such as PLS-CADD and SAPR LEP.*

4.1. The ”Kurzeme Ring” project

The ”Kurzeme Ring” (KR) is the first strategically important transmission system infrastructure project commenced in the restored Republic of Latvia, with the status of an object of national interest. The KR is part of an overall EU co-financed *Baltic Interconnection Plan* (*BEMIP*) within a larger project for strengthening the Baltic power transmission safety, the *”NordBalt”*, the implementation of which foresees construction of an interconnection between Lithuania and Sweden (a submarine cable), as well as strengthening the Latvian and Lithuanian PTNs in order to improve the power supply reliability to all the Baltic countries, increase the power transit of their interconnection and develop the required lacking transmission capacity in Latvia. Implementation of the international power infrastructure development project will result in the development of the Baltic electricity market, ensuring the possibilities of buying, selling and transit of electricity with other EU countries. It is essential to point out that the construction of KR will ensure sufficient power supply reliability to the region of Kurzeme, thus diminishing the probability of emergencies in the transmission system; also, the possibilities of operative elimination of emergencies will increase, considering the potential for connecting new electricity utilization equipment [44].

4.2. The prospectives and possibilities of using high-temperature conductors

This subchapter will review and analyze the results obtained in the technical and economic comparison of HTLS and ACSR type conductors for OHL examples based on the following:

1. the initial data of action 1 of the „Kurzeme Ring" project, for example, the 110 kV OHL design of the branch to substation „Aizpute" (see further) [45] whereas an analysis of the calculation results for the other discussed OHL examples can be found in [46, 47] – for the 330/110 kV basic line (within the Kurzeme Ring pre-project); [48] – the 110 kV OHL design of the branch to substation „Alsunga";
2. the initial data of existing OHLs of the Latvian PTN, for example, line No. 355 and line No. 309 [49].

The comparative calculations have been conducted both based on the technical aspect of the selected conductors – their mechanical restrictions (maximum permissible (σ_{max}), minimum permissible (σ_{min}) and operating ($\sigma_{eksp.}$) stresses in the conductor; wind, weight and clearance spans; conductor sags), thermal restrictions (OHL throughput capacity; permissible conductor temperatures) – and the economic aspect (savings depending on the number of intermediate towers, calculation of the total costs of required materials and equipment), based on the initial data of a corresponding OHL example – the climatic conditions for OHL designing (wind speed; icing thickness; maximum, minimum and operating temperature characteristic of the selected OHL region), the specific structural parameters (design span length; clearance to the ground or to crossed objects), the required structures (conductors and protective wires, line fittings, towers and foundations) and the design conditions, considering the valid standards.

For example [45], for the 110 kV OHL No. 266 within the project, the branch to the substation *„Aizpute"*, which is included in the Kurzeme Ring project (action 1), the results obtained from the technical comparison are shown in Fig. 4.1, 4.2, and the results of the economic comparison are shown in Fig. 4.3. As a result it can be concluded that:

1) The stress of a conductor for the conductor heat-up mode at +35 °C for *Glasgow* and *Casablanca* conductors (aluminium conductor composite core – ACCC), and *Hawk 477* (aluminum conductor composite reinforced – ACCR) is higher as compared with the traditional type conductor – *AS-240/32* and *242-AL1/39-ST1A* (aluminium conductor steel reinforced – ACSR), which means that *Glasgow*, *Casablanca* un *Hawk 477* conductors will have smaller conductor sags (see Fig. 4.1);
2) the wind span (L_{wind}) is the decisive span of all the described conductors, as the main condition for the layout of towers on the OHL route (the need to comply with the standard ground clearances), for example, L_{wind} of an *AS-240/32* type conductor is 403.6 m, which is the worst parameter as compared with the clearance span (L_{cl}), which is 436.5 m at a temperature of +35°C. The conductor *Casablanca* is preferable, because the maximum allowable wind span is 425.4 m, which is by about 25 m more than in the case of using the *242-AL1/39-ST1A* conductor, or by about 22 m more than in the case of using *AS-240/32* and *Hawk 477*, and by about 16 m more than in the case of using the *Glasgow* conductor, if all the other conditions remain the same (see Fig. 4.2).

3) concerning the analysis of thermal limitations, it can be concluded that the HTLS type conductors, for example, *Glasgow*, *Casablanca* and *Hawk 477*, have higher maximum permissible conductor temperatures as compared with the *AS-240/32* and *242-AL1/39-ST1A* conductors (ACSR), which means that HTLS type conductors ensure the installed capacity (in this case, the load current is assumed at 850 A) with one conductor per phase, for example, if the conductor *Casablanca* is used, then its permissible rated operating conductor temperature is 120°C and as a result it provides 922 A with one conductor per phase, whereas in comparison with the *AS-240/32* conductor, two conductors per phase are required, because the permissible operating temperature of this conductor is only 70°C [23];
4) the OHL capital investments in the case of using the *AS-240/32*, *242-AL1/39-ST1A* and *Hawk 477* (ACCR) turned out to be higher than using the HTLS type conductors – *Casablanca* and *Glasgow* (ACCC). The difference between *AS-240/32* and the *Glasgow* and *Casablanca* conductors is about 2.8 %, as compared with *Hawk 477*, where it is 3.9%. As a result, in the case of using the *Casablanca* conductor was selected as the optimum variant with the minimum capital investments – 84180 r.v./km, then follows the *Glasgow* conductor – 85960 r.v./km, then there are the *242-AL1/39-ST1A* and *AS-240/32*conductors, and the last one is the *Hawk 477* conductor – 87480 r.v./km (see Fig. 4.3).

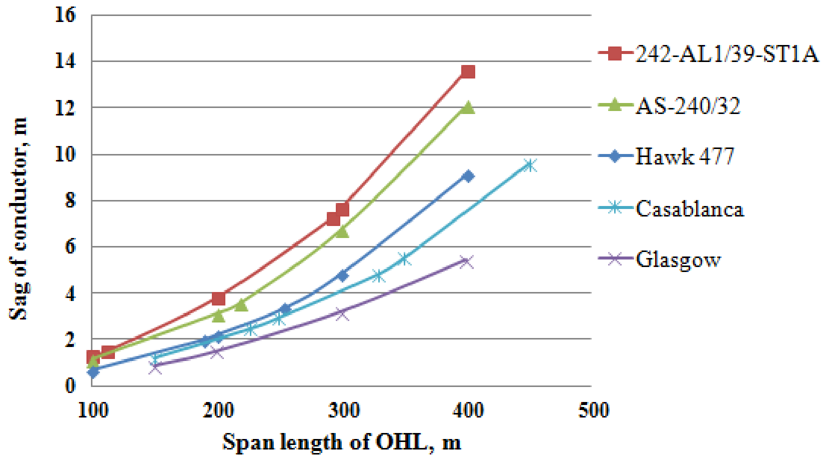
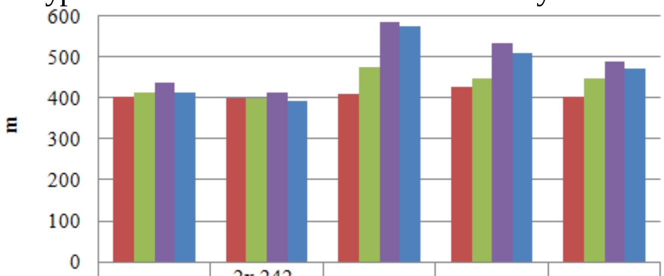


Fig. 4.1. The tension-lenght relationship in conductor heat-up mode at +35°C of the different types of conductor of line No. 266 analysis



	2xAS-240/32	2x 242-AL1/39-ST1A	1x Glasgow	1x Casa-blanca	1x Hawk 477
Lwind	403.6	400.0	409.3	425.4	403.4
Lweight	414.3	400.0	476.3	446.1	445.8
Lcl at +35°C	436.5	411.8	585.9	533.3	487.4
Lcl at +70°C	414.0	393.0	574.9	508.2	470.1

Fig. 4.2. The allowable wind (L_{wind}), weight (L_{weight}) and clearance (L_{cl}) spans of both regimes of the different types of conductor of line No. 266 analysis

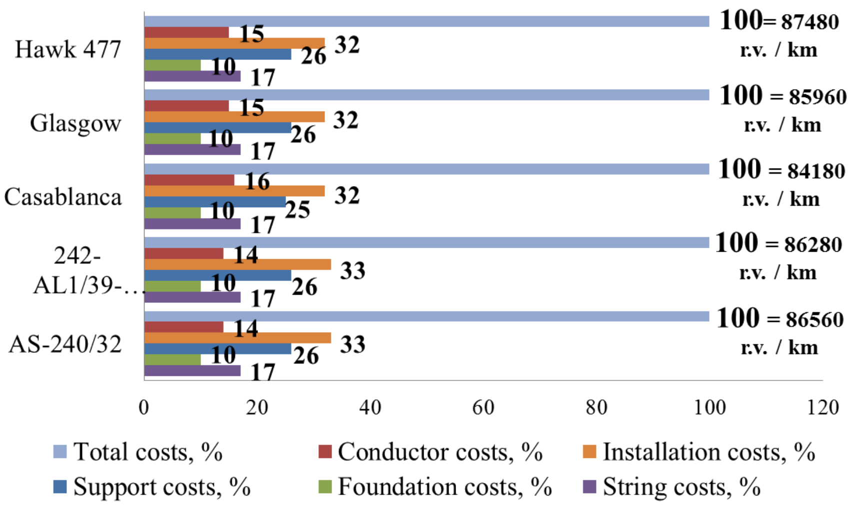


Fig. 4.3. OHL line No. 266 capital investments

4.3. The results of the optimization of the OHL of the ”Kurzeme Ring” project

The OHL example, which used the above-described OHL designing optimization approach (see Chapter 2), is based on the example of a real-life „Kurzeme Ring” project (action 1), which includes 330/110 kV OHL construction [29].

The power system analysis for the regional development scenarios has resulted in the following alternatives for a new transmission line:

- 110 kV OHL with a maximum current of 1200 A (optimistic scenario 1) or 800 A (pessimistic scenario);
- 330 kV OHL with a maximum current of 2000 A (optimistic scenario 2) or 1500 A (pessimistic scenario).

As a result, for this new OHL, the task of structural and parametrical optimization was formulated.

After searching for the optimum solutions using the software for OHL design – PLS-CADD [3], twenty alternatives were selected, with different combinations of towers and conductors (HTLS and ACSR type conductors). To simplify the posed task, at the first stage, instead of NPV maximization, minimization of the invested capital has been performed, while in the final comparison of the alternatives, the time-consuming task with the NPV criteria was used.

The height of the towers, the span lengths, the ground clearances and the clearances to the crossed objects define the parameters of the EF and MF, the values of which are regulated with the purpose for decreasing the impact on the environment. For simplifying the evaluation of this impact, the calculations of the EF and MF were done by using special software (see Fig. 4.4 a) and b)) [50]. As a result, summarizing the MF and EF indicator calculation results, it can be concluded that the MF intensity fully complies with the existing standards, whereas the EF intensity may diverge from the set requirements at the ”bottlenecks” of the PTN. In order to solve the existing problem, an optimum solution of the OHL project implementation, which is laid out below, was proposed.

Then, choosing the conductor and tower types, we selected the following alternatives:

a) A1 and A10; A11 and A20 means that traditional type conductors are used both for the 110 kV OHL circuits and the 330 kV OHL ones;
b) A6…A9; A16…A19 – HTLS conductors are used both for the 110 kV OHL circuits and the 330 kV OHL circuits;

c) A2…A5; A12…A15 – traditional type conductors are used in combination with HTLS conductors for the 110 kV and 330 kV OHL circuits (see Fig. 4.5).

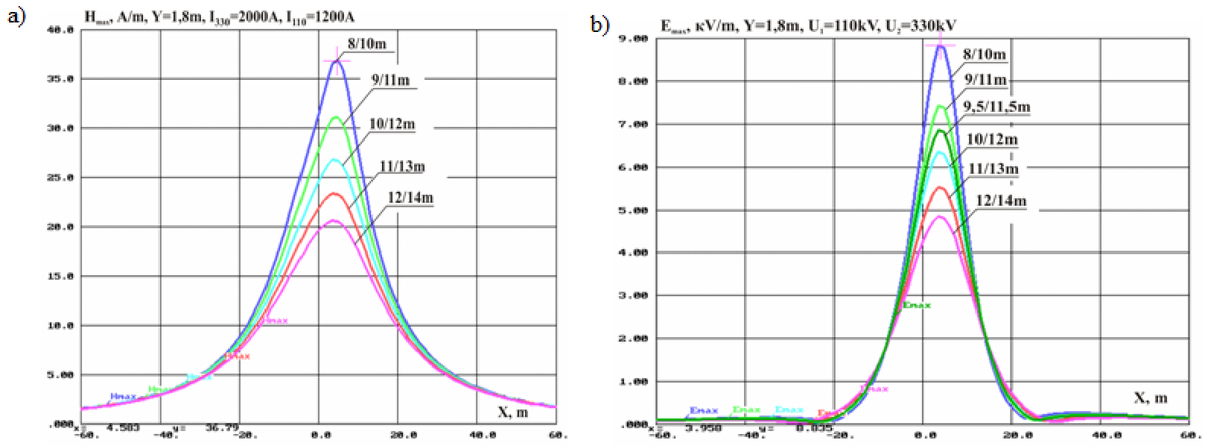


Fig. 4.4. The OHL distributions of MF (a) and EF (b) at Y = 1.8 m above ground in the cross-section of a 330/110 kV line for minimum clearance of the 330/110 kV conductors: 8/10 m, 9/11 m, 9.5/11.5 m, 10/12 m, 11/13 m and 12/14 m

The obtained results of optimum solution for the two-objective OHL optimization (a two-dimensional plane was constructed after twenty alternatives) based on Pareto's approach [51], where I_C (p.u.) is the invested capital and E (kV/m) is the strength of the electrical field, which in this example is defined as the most impacting OHL designing restriction, are shown in Fig. 4.5. Evaluating the previously selected twenty alternatives by means of Pareto's approach, we find that the competitive alternatives are A6, A7, A9, A10, A15, A17, A19 un A20. For further consideration only the competitive alternatives are left, using here the more time-consuming and more precise NPV method instead of the simplified analysis of capital investments (see Table 4.1).

As a result, the analysis reveals the following:

- In case of using the "classical" problem – namely, NPV maximization complying with all the OHL restrictions – alternative A10 should be chosen. The final decision will be taken using and analyzing the criteria of mechanical, thermal and environmental restrictions;
- If violation of one of the restrictions is allowed, alternative A17 or A19 should be chosen taking into account the probability of occurence of such a restriction.

Table 4.1

Expected NPV and restriction indices Pr_i

Alternatives	Optimistic scenario 1	Pessimistic scenario 2
	$NPV_{11}\|\|R_{11}$	$NPV_{11}\|\|R_{11}$
A10	4.7 // 6.9	5.4 / 5.0
A17	6.2 // 7.1	5.33 / 5.6
A19	6.7 // 8.0	5.7 / 7.3

The risks of emergence of conditions leading to operational changes (and, therefore, to additional economic losses) were estimated from the viewpoint of making the final decision. Violation of restrictions on the electrical field strength for the considered example under the Latvian climate can arise at the maximum air temperature of +35°C and the maximum load current. The combination of these two conditions is hardly probable: for alternative A10 it is

0.01, while for alternative A17 – only 0.000001 (both probabilities are estimated considering the optimistic scenario). After taking into account the above-mentioned probabilities, alternative A17 would be chosen as the final decision for practical implementation of the OHL project; besides, to satisfy the relevant legislative conditions for the electric field, permanent monitoring and operating of OHls is needed.

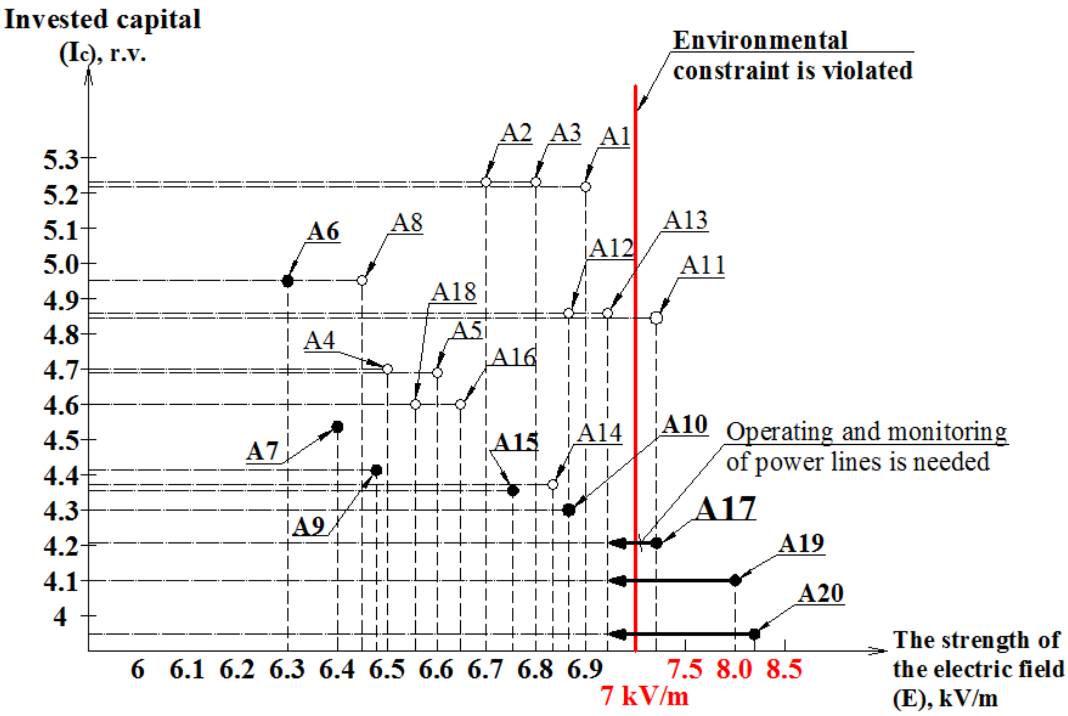


Fig. 4.5. Pareto's set for the alternatives, constructed according to the selected alternative combinations fot the OHL project realization

4.4. Optimization of the OHLs within the "Kurzeme Ring" project with a coalition foundation example

This study is dedicated to the second particular case (see Subchapter 2.6), making the additional assumption that it is possible to form a coalition with the other company. In most cases a mutual benefit is expected. The proposed strategy is based on the "Kurzeme Ring" project (action 1) example, where it is assumed that two independent companies are engaged in the creation of the power transmission line project. One company is engaged in the creation of a 110 kV transmission line and the other – of a 330 kV transmission line. Therefore, first and foremost, the alternatives that are advantageous for each company have to be chosen as the decision. It is also necessary to show the capital investments of the project and the potential benefit for each company in the case of an individual approach, implementing the whole project separately, and check if it is possible to form a coalition. Then there is the task of analyzing the outlook for forming coalitions with other companies.

Taking into account the assumption that the 110 kV OHL has to transmit a current of 1200 A, while the 330 kV OHL – 2000 A, and based on the pre-design base of the "Kurzeme Ring" project (action 1), the capital investments of the three general variants were evaluated (see Fig. 4.6):

1. There is a single-circuit 110 kV overhead line with a steel aluminium conductor *AS-240/32*; a phase is divided into two conductors (*2xAS-240/32*), as a result, such a variant provides a current of 1210 A;

2. There is a single-circuit 330 kV overhead line with a steel aluminium conductor *AS-400/51*; a phase is divided into three conductors (*3xAS-400/51*) with an installed ampacity of 2475 A;
3. There is a cooperative circuit, which consists of a single-circuit 110 kV OHL with a *2xAS-240/32* conductor – 1210 A; and a 330 kV OHL with a *3xAS-400/51* conductor – 2475 A.

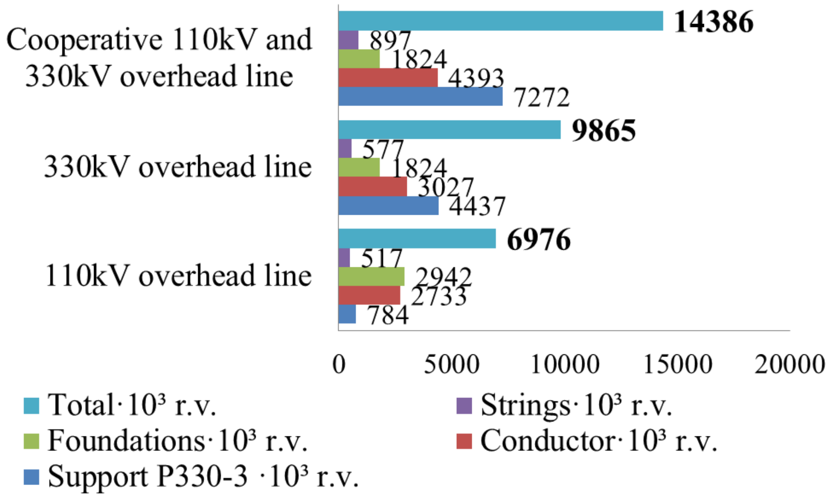


Fig. 4.6. OHL capital investments in accordance with the selected variant

The OHL capital investments as the main economic aspect were calculated for each variant (see Fig. 4.6). Analysing the obtained results, the following can be concluded [52]:

I. If there is an individual approach to the OHL project, when company A constructs its own 110 kV high voltage PTL and company B – its own 330 kV OHL (see Fig. 4.6), the required total capital investments of the OHL project for each company in the case of individual behaviour are presented in Table 4.2;

Table 4.2

OHL capital investments in the case of individual behaviour

Company	Investments, r.v.
A	6976000
B	9865000
Total capital investments for A and B	**16841000**

II. If there is OHL project implementation in the case of organizing a coalition of two companies and distributing the additional revenue by using the Shapley value, which requires agreement and approval of both companies, the project companies A and B organize a coalition (two companies that divide the additional revenue in half), and in this case, the 110 kV and 330 kV OHL cooperative circuit is placed on one OHL route (see Fig. 4.6). As a result, the required total capital investments of transmission line construction for both companies in the case of cooperative behavior are presented in Table 4.3.

Table 4.3

OHL capital investments in the case of cooperative behaviour

	Investments, r.v.
Coalition of companies A and B	14386000
Additional revenue for each company	1227500
Total additional revenue for companies A and B	**2455000**

It is obvious that in case of cooperative behavior, the investments of the OHL project diminished reduced considerably. This means that the formation of such a coalition is rational and possible in terms of economy of investments. It is worth noting that in the real-life project the revenue is the amount of tens of millions EUR.

5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

5.1. Overall conclusions

1. The role of OHLs in contemporary power industry is quickly increasing, since development of PTNs is anticipated both on an international scale and nationally, thus, on the one hand, it will be necessary to expand the electrical connections of the existing network by constructing new OHLs with a high throughput capacity; on the other hand, it will be possible to solve these problems by developing and implementing new technologies in the existing power network (for example, OHL thermal load current monitoring systems, HTLS conductors), which enable optimization of the operation, service and control of OHLs.
2. In order to be able to solve the OHL optimization task, it is necessary to take into account the specific OHL structures and parameters, which form their mechanical, thermal and environmenal impact restrictions, achieving as a result a technically and economically substantiated optimum OHL design solution for its practical implementation.
3. In the designing of OHLs, it is necessary to use modern computer software complexes; for example, the present paper uses PLS-CADD and SAPR LEP, which makes it possible to perform the required calculations and to appropriately analyze the obtained results efficiently and quickly, meeting all the basic requirements set by the OHL designing task.
4. Considering the newest tendencies in the development of power systems, which considerably impact the PTN planning and development process, a need arises for new OHL optimization approaches, which will make it possible to alleviate the decision-making process in PTL designing optimization tasks, as a result diminishing the amount of investments and the power losses, as well as improving the reliability of the system and the quality of transmitted electricity.
5. In order to solve the OHL designing optimization problem, a multicriterial optimization task is formulated, which takes into account a large number of state and decision variables as well as the possible influence of probabilistic and uncertain parameters.
6. The paper proposes a multicriterial OHL optimization method, which is partially based on the stochastic approach and game theory criteria, which ensures the possibility to consider even the alternatives with violations of the most impacting constraint, yet which with some additional measures may represent the most cost- effective OHL design solution.
7. The proven rationality of using the multicriterial OHL task solution approach is based on on an example of 1st stage design within the ”Kurzeme Ring” project; as a result, it can be concluded that the proposed method using the singling out of the set of Pareto’s decisions, makes it possible to evaluate the costs of improving the environmental impact indicators and fosters the adoption of substantiated decisions.
8. The study comprises testing of thermal load current estimation methods, based on direct monitoring of the principal OHL parameters (experimental data) as well as indirect monitoring (calculation data), comparing the measured and calculated conductor

temperatures and sags at a number of operating modes of existing OHLs at the given weather conditions, in order to determine the most appropriate (exact) thermal load current estimation method (from the thermal point of view).

9. As a result of analyzing a number of verification models of the OHL allowable load current monitoring system, the most appropriate method, MT 34-70-037-87, emerged; thus, by using the theoretical basis of this method, the permissible conductor temperature and thermal load current were determined, based on the results of both measurements and calculations.
10. As a result, the study proposes a synthesized OHL allowable thermal load current monitoring algorithm, the operation of which is based on the substantiation of verification results for various OHL examples, considering the thermal, mechanical and environmental restrictions.
11. The use of the proposed algorithm makes it possible to improve the accuracy of estimating the allowable load current value for existing OHLs or OHLs under design, as well as to determine the hidden load current reserve (evaluation of the possible OHL additional clearance), resulting in an opportunity to considerably increase the transferred power of the OHL, determining a precise allowable OHL conductor temperature at exact weather conditions. Besides, using actual conductor temperature data would make it possible to regulate the OHL allowable load current in a more flexible way, adapting to dynamically operative monitoring and control of high-voltage power lines in real-time mode and giving new opportunities for the integration of the smart grid.
12. The proven technical efficiency of the used synthesized OHL allowable load current monitoring algorithm for considering various problems makes it possible to diminish the total amount of investment into the reconstruction of the existing OHLs, becoming an economically substantiated solution for improving the existing PTN.
13. Integration of new technologies, for example, the use of high-temperature composite core conductors (HTLS type conductors), is an effective technically and economically promising solution in modernizing the existing OHLs.
14. The proposed solution has been tested by practically applying various OHL examples, including the OHLs of the ”Kurzemes Ring” project as well as examples from the existing Latvian power transmission network, analyzing the results of the technical and economic comparison of HTLS and ACSR type conductors, taking into account the mechanical and thermal restrictions for OHLs. Besides, this solution could be still more economically substantiated if the price of HTLS type conductors were diminished.
15. Methods based on the game theory and its criteria can contribute to making the right decision about the development of power transmission and energy supply sources.
16. The cooperative game theory is applied to the solutoin of a variety of power-industry tasks, where independent power companies can gain a high level of profit by forming a successful coalition with other market participants.
17. The proposed synthesized method of OHL capital investment distribution has been tested by using the example of an OHL from the Kurzeme Ring project (action 1) in practical application. The results obtained in the study substantiated the rationality of forming a coalition from the power companies involved in the OHL project and the possible advantages in terms of investment savings.

5.2. Recommendations for future work

The proposed methods for optimizing the existing OHLs and OHLs under design are becoming particularly topical at the current situation within the power industry, when the development of power systems is being promoted by adapting to the tasks of the smart grid concepts. Therefore, considering the generally accepted future vision tendencies in the power industry, mainly regarding the technical and economic solutions for the develoment and improvement of OHLs (the optimization methods), in future work it is necessary to aim at the development and modernization of the following tasks:

1. To modernize the developed OHL designing optimization algorithm, which substantiates the multicriterial statement of the OHL designing task with the use of Pareto's approach and the scenario approach for the adoption of the final decision, introducing it in the form of computer software implementation;
2. To develop the synthesized system/ terminal for monitoring the allowable load current of OHLs (from the thermal point of view), by introducing additional calculation blocks into the algorithm, accounting for the replacement of the existing OHL conductors with high-temperature conductors, thus expanding the boundaries of the allowable temperature and load current values of the conductor, additionally evaluating the probability of occurrence of operating and emergency modes at the set climatic conditions;
3. To assess the cases when it is necessary to place such OHL allowable load current monitoring systems/ terminals at the ”bottlenecks” of the existing Latvian PTN, which would make it possible to minimize capital investments in the reconstruction of the high-voltage lines to be used;
4. To evaluate the influence of the foreseeable climate change on the throughput capacity of the high-voltage power lines in Latvia.

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