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IMPACT OF LIMITATIONS AND A SUPPORT ON THE ELECTRICITY MARKET, PRICES AND REGIMES

Summary of the Doctoral Thesis

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DOCTORAL THESIS
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To be granted the scientific degree of Doctor of Engineering, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 11 October, 2017 at the Faculty of Power and Electrical Engineering of Riga Technical University, 12/1 Āzenes Street 12/1, Room 306.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Inga Iljina .... (signature)

Date ....

The Doctoral Thesis has been written in Latvian. It consists of Introduction, five chapters, Conclusion, Recommendations, 82 figures, 18 tables and 5 appendices. The total number of pages is 162. The bibliography contains 151 sources.

CONTENT

Topicality of the Doctoral Thesis

The restructuring of power engineering sector that is taking place in the world encourages the emergence of energy markets. The reforms in power engineering sector have caused a transition to competitive price formation mechanisms on energy market. The traditional centralised management of the sector is superseded by management that is based on adequate reflection of price signals of market subjects. In order to be able to judge about this process, it is necessary to review the development of the sector. To form a complete picture, it is necessary to investigate the advantages and disadvantages of various market models. Latvia's joining the energy market determines the need to change the principles of power system management. The efforts to achieve an effectiveness level as high as possible lead to the creation of a corresponding software complex. To achieve this goal, it is necessary to solve many labour-intensive problems and tasks.

On an ideal electricity market, all of its participants buy and sell electricity at a unified equilibrium price. The price formation is influenced by many factors and restrictions (technical, legal and environmental ones). The restrictions can be at least partially changed. Society uses the restrictions to influence the development of the power supply system and to direct it towards the desired goal (for example, diminishing of emissions or regional development) or diminish the amount of imported energy resources. If restrictions of various kinds are observed, including the wish to support the use of renewable energy resources, in many cases a unified equilibrium price for all the market participants cannot be determined. Compliance with the restrictions may require considerable means. The support in the form of increased electricity purchase prices leads to deviations of the regime management of renewable energy resources from the optimal operating regimes on the market that is free from support and restrictions. Questions arise as to how substantiated are the support prices and restrictions. Therefore, to understand the operation of the electricity market, additional attention has to be paid to the market restrictions and price formation mechanism. In order to be able to judge the influence of the restrictions, it is necessary to solve a complicated task of optimisation of power system regimes.

The presented Thesis addresses the issues of formulating and solving the optimisation tasks, which have been widely discussed in literature worldwide. A considerable contribution to the development of optimisation theory of power systems has been made by such researchers as F. C. Shveppe, S. M. Harvej, V. V. Hogan, S. Stoft, G. B. Sheble, L. A. Krumm, P. I. Bartolomej, N. I. Voropaj, A. Z. Gamm, M. Bjorndal, B. Burstede, T. J. Panikovska, R. Green, V. Neimane and others. Such Latvian researchers as J. Barkans, Z. Krisans, J. Gerhards, A. Sauhats, A. Mahnitko, G. Junghans, O. Linkevics, I. Oleinikova, A. Mutule have contributed to the investigation of power system operation and electricity prices in the conditions of a liberalised market.

The adopted market conditions and the presence of competition have considerably changed the formulation and the significance of optimisation tasks. These tasks are practically being solved hourly, adapting the regime of a certain producer to the changeable market conditions. It is necessary to forecast the operating conditions and the behaviour of the competitors, to account for the random and indeterminate factors and processes, and to simulate production conditions and processes. Inaccuracy in calculations causes direct economic losses.

The topicality of all the above aspects has determined the choice of the subject, goals and contents of the presented Thesis.

The Goal and the Tasks of the Doctoral Thesis

The goal of the Thesis is to contribute to economically efficient operation and development of power system. To reach this goal, the Thesis addresses the following main tasks:

1. To review the development of electricity markets and the operation principles of the largest deregulated electricity markets.
2. To investigate the principles of electricity price determination in the conditions of a competitive market.
3. To do the synthesis of a stochastic algorithm of power plant regime and optimisation of supply price. The objective function of the task has been transformed and the optimisation task has been decomposed, which made it possible to use a combination of linear and non-linear programming, ensuring an acceptable calculation time.
4. To develop an algorithm for calculating electricity node prices in a steady-state regime, considering the inhomogeneity of the network and reactive power flows; to approbate the algorithm by way of experimental calculations.
5. To substantiate the method and algorithm for analysing the influence of the transmission limitations of the power system and the technical and legal restrictions of power plants on the regimes and electricity prices.
6. To define the deficiencies of the adopted support schemes for renewable energy resources; ways to eliminate these are proposed.
7. To propose and test the method and the algorithm for simplifying the solution of the price calculation tasks for non-linear nodes.

Links of the Thesis to Other Research in Power Engineering Done in Latvia

Latvia's voluntarily joining of energy market determines the need to change the control principles of power system. Efforts to achieve as high an effectiveness level as possible lead to the creation of a corresponding software complex for the regime control. To achieve this goal, it is necessary to solve many labour-intensive problems and tasks. In order to do this and to create the required software as quickly as possible, the problem is divided into several parts, which are solved within a series of studies:

a) Control of fast processes (short circuit, loss of synchronism, frequency emergencies);
b) Optimal planning and control of short-term regimes;
c) Strategic planning of the development of power systems (long-term planning);
d) Simulation of the regimes of power plants and networks.

Over the recent years, many doctoral theses in mentioned areas have been defended or prepared for the defense in Latvia (A. Kutjuns, G. Junghans, O. Linkevics, M. Kalnins, D. Zalostiba, G. Vempers, V. Strelkovs, S. Kiene, A. Gavrilovs, J. Kucajevs, M. Silarajs, N. Skobeleva, A. Lvovs, R. Petricenko, S. Berjozkina, R. Varfolomejeva, A. Obusevs, L. Petricenko, H. Coban). These studies were part of the National Research Program "Energy" (under the scientific guidance of academician J. Ekmanis). By using the amassed experience and the synthesized algorithms, a new goal was set – to synthesize a complex software for the regime control of power system. The presented Thesis complies with the above-mentioned goal.

Methods and Means of the Research

1. The linear programming optimisation tasks were solved by means of the simplex method.
2. The non-linear programming optimisation tasks were solved by means of the generalised reduced gradient method, Quasi-Newton method and the linear approximation of the non-linear task, which made it possible to simplify the solution of the problem and use the simplex method.
3. The node price calculation was done by means of the Lagrange method of uncertain multipliers.
4. Also, the principle of the duality of linear programming tasks was used for the node price calculation for a linear programming task in a homogeneous network.
5. The basic optimisation tasks of the Thesis were solved in Microsoft Office Excel® and MatLAB® environments, using their built-in solvers.
6. The calculations were done by using the MatLAB® interactive environment, which is intended for intensive computing, analysis and visual reflection of data, as well as the MathCAD® software, which is intended for solving engineering problems and visualisation and analysis of the results.

Scientific Novelty and Main Results of the Thesis

1. The principles of electricity price determination in the conditions of a competitive market have been investigated.
2. An algorithm and a mathematical model for solving the power system optimisation task and calculating the zone (node) price of electricity, considering the inhomogeneity of the network and the reactive power flows has been developed and approbated using the Baltic Power System as an example.
3. The possibility to use linear approximation for solving complex non-linear power system optimisation tasks has been substantiated. The approbation of the method has been done for the task of distribution of power flows among power plants, which is used to determine the node prices.
4. The sensitivity of the prices of electricity zones (nodes) to the restrictions of the power system transmission network has been analysed and the influence of these on the electricity price has been substantiated.
5. The possibility of formulating and solving the optimisation task in a stochastic way has been proved, by decomposing the task and using a combination of linear and non-linear programming algorithms.
6. The need for changes in the support schemes of biofuel plants and small hydropower plants has been proved.

Practical Significance of the Thesis

The algorithms proposed in the Thesis can be used:

1. By dispatchers, for operational control of the regimes of the power system;
2. By electricity producers, for forming price bids and for day-to-day planning of the regimes of power plants (using the developed algorithms and mathematical models will make it possible to increase the production efficiency of the generation sources);
3. By electricity traders, when planning the electricity purchase expenses;

4. By power engineering specialists, who do the development planning and designing of power systems (both for planning the development of power supply networks and analysing the development alternatives of the generating capacities of the system);
5. Energy sector policy makers when developing or changing the support schemes for energy resources.

The results of the presented Thesis are used in completed or ongoing projects and programs:

1. National Research Programme “Energy” (scientific supervisor Academician J. Ekmanis) Project No. 7 “Climate change mitigation and renewable energy technology integration in Latvian power system” (scientific supervisor Professor A. Sauhats);
2. National Research Programme “Energy efficient and low-carbon solutions for a secure, sustainable and climate variability reducing energy supply” (LATENERGI) (scientific supervisor Aademician L. Ribickis) Project No. 2 “Power system development planning and energy production, sale and distribution optimization” (scientific supervisor Professor A. Sauhats);
3. Research "Development of the plannning software for the JSC “Latvenergo” power plant regimes" (on the contract basis signed by Riga Technical University and JSC “Latvenergo” in 2013, research completed in 2016). The software was developed by a group of researchers from RTU and Latvenergo with participation of the author of the presented Thesis.

The results are also used in the in the learning process of master students in the subject “Optimization of power systems”.

Author’s Personal Contribution

Power system optimization and nodal electricity pricing under market conditions, and verification and substantiation of use of approximatory programming for power system optimization was chosen as the research direction with support from Professor Anatolijs Mahnitko.

Formulation of stochastic task and its addressing algorithm, application of Shapley vector was defined with support from Professor A. Sauhats.

Analysis of the renewable energy support schemes has been carried out jointly with Senior Researcher R. Varfolomejeva. The collective results of publications that belong to R. Varfolomejeva (see the list of scientific papers), are not included in the presented Thesis, except the optimization results of small cogeneration plants and hydropower plant, which are noted in the text. The analysis of the Daugava HPP cascade was done using the software OPTIBIDUS, which was developed and improved at the Institute of Power Engineering of RTU (Director A. Sauhats, responsible researchers: K. Baltputnis and R. Petričenko). The software was developed on the basis of the hydropower plant optimization algorithm.

Other calculations, results analysis, programming and testing of optimization procedure, results presentation, conclusions and summary, which are included in the Thesis were developed by the author.

Approbation of the Results of the Thesis

The main results of the research were presented and discussed at 17 International scientific conferences:

1. The 10th International Conference on Engineering of Modem Electric Systems, Romania, Oradea, 27–29 May, 2009.
2. The 5th International Conference on Electrical and Control Technologies ECT-2010, Lithuania, Kaunas, 6–7 May, 2010.
3. The 9th International Scientific Conference “Energy – Ecology – Economy 2010”, Slovakia, Tatranske Matliare, 18–20 May, 2010.
4. The 8th International Conference on Advances in Electro-Technologies ICAdET′2010, Romania, Oradea, 27–28 May, 2010.
5. The XI International Scientific-Technical Conference “Problems of Present-day Electrotechnics-2010”, Ukraine, Kiev, 1–3 June, 2010.
6. The 51st International Scientific Conference of Riga Technical University on Power and Electrical Engineering, Latvia, Riga, 14 October, 2010.
7. The 6th International Conference on Electrical and Control Technologies ECT-2011, Lithuania, Kaunas, 5–6 May, 2010.
8. The 10th International Scientific Conference "Energy – Ecology – Economy 2011", Slovakia, Tatranske Matliare, 7–9 June, 2011.
9. The 3rd International Student Conference on Energetics 2011, Portugal, Leiria, 7–9 July, 2011.
10. The 7th International Conference on Electrical and Control Technologies ECT-2012, Lithuania, Kaunas, 3–4 May, 2012.
11. The 11th International Conference on Environment and Electrical Engineering EEEIC 2012, Italy, Venice, 18–25 May, 2012.
12. The 13th International Scientific Conference on Electric Power Engineering 2012, Czech, Brno, 23 – 25 May, 2012.
13. IEEE Grenoble PowerTech 2013, France, Grenoble, 16–20 June, 2013.
14. The 12th International Conference on Environment and Electrical Engineering EEEIC 2013, Poland, Wroclaw, 5–8 May, 2013.
15. IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives, Latvia, Riga, 11–13 May, 2015.
16. The 15th International Conference on Environment and Electrical Engineering EEEIC 2015, Italy, Rome, 10–13 June, 2015.
17. The 16th International Conference on Environment and Electrical Engineering EEEIC 2016, Italy, Florence, 7–10 June, 2016.

Scientific Papers

The main results of the research are published in 32 international publications:

1. Mahņitko, A., **Umbraško**, I. Determination of Electricity Nodal Prices Using Lagrange Method. *Journal of Computer Science and Control Systems*. 2009, vol. 2, no. 2, pp. 161–166.
2. Mahņitko, A., Gerhards, J., Ribakovs, S., **Umbraško**, I. Pricing Questions in the Electric Power Markets. *Power and Electrical Engineering*. 2009, vol. 24, pp. 16–23.
3. Mahņitko, A., **Umbraško**, I. Influence of System Limitations on the Electricity Prices at Consumption Nodes. *Latvian Journal of Physics and Technical Sciences*. 2010, vol. 47, no. 4, pp. 3–16.

4. Mahņitko, A., **Umbraško**, I., Varfolomejeva, R. The System's Limitations Costs Determination Using the Duality Concept of Linear Programming. *Journal of Computer Science and Control Systems*. 2010, vol. 3, no. 1, pp. 115–118.
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7. Mahņitko, A., **Umbraško**, I., Varfolomejeva, R. About Electricity Consumers Bid Formation. In: *ПСЭ-2010*, *Ukraine*, *Kiev*, *1–3 June*, *2010*. Kiev: KPI, 2010, pp. 1–4.
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10. Mahņitko, A., **Umbraško**, I. Technological Limitations Influence on Value of Objective Function of Electric Power System Optimisation Task. In: *The 51st International Scientific Conference Power and Electrical Engineering. Section of Power and Electrical Engineering: Abstract Book and Electronic Proceedings*, *Latvia*, *Riga*, *14 October*, *2010*. Riga: RTU, 2010, pp. 111–114.
11. **Umbraško**, I., Varfolomejeva, R., Mahņitko, A. The Electricity Producers Bid Prices Formation based on Profitability. In: *The 10th International Scientific Conference "Energy-Ecology-Economy 2011"*, *Slovakia*, *Tatranske Matliare*, *7–9 June*, *2011*. Bratislava: Slovak University of Technology, 2011, pp. 1–6.
12. Mahņitko, A., Varfolomejeva, R., **Umbraško**, I. The Market Participants Profit Maximization Considering the Spinning Reserve and System's Limitations. In: *The 15th International Scientific Conference on Present-day Problems of Power Engineering. Vol.3: Forecasting and Energy Economics: Forecasting, Planning and Development Issues, Energy Markets and Technical-Economic Analysis*, *Poland*, *Jurata*, *8–10 June*, *2011*. Gdansk: Department of Electrical Power Engineering, 2011, pp. 43–50.
13. Mahņitko, A., **Umbraško**, I., Varfolomejeva, R. Nodal Prices Determination Using the Duality Concept of Linear Programming. In: *Electrical and Control Technologies 2011: Proceedings of the 6th International Conference on Electrical and Control Technologies*, *Lithuania*, *Kaunas*, *5–6 May*, *2011*. Kaunas: Technologija, 2011, pp. 149–154.
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27. Coban, H., Varfolomejeva, R., Sauhats, A., **Umbraško**, I. Hydropower Plant Regime Management According to the Market Conditions. In: *2nd International Congress on Energy Efficiency and Energy Related Materials (ENEFM2014): Book of Abstracts*,

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Structure and Description of the Doctoral Thesis

The presented Doctoral Thesis is written in Latvian. It consists of an introduction, five chapters, conclusion and recommendations, a bibliography, 82 figures, 18 tables, 5 appendices. The total number of pages is 162. The bibliography contains 151 sources.

Chapter 1 reviews the course of development of electricity markets and gives analyses of the advantages and disadvantages of various models of electricity trade. This chapter is dedicated to various principles of determining electricity price in the conditions of market competition and limitations. Zonal price and nodal price determination mechanisms are compared. Particular attention is paid to the major deregulated electricity markets. The situation in electricity market in the Baltic countries is reviewed, paying attention to the transmission capacity of inter-zonal electrical lines as well as the possibilities of eliminating these limitations.

Chapter 2 discusses the mathematical foundation of algorithmization of the planning task of power system regime, determines the stages in the solution of the multi-dimensional task, and reviews a wide range of mathematical programming methods. A methodology for calculating complicated power-industry planning processes has been proposed and substantiated.

Chapter 3 addresses the task of optimization of the regimes of biogas power plants, considering the market prices and limitations.

Chapter 4 reviews the possibilities of optimizing a HPP cascade by considering the limiting factors.

Chapter 5 contains examples of power system regime planning and electricity price determination tasks, which comprise both linear and non-linear programming tasks. It proposes an algorithm for solving the power system optimization task for non-uniform network and determining the nodal prices by using Lagrange's method of indeterminate multipliers. The impact of the limitations of the transmission capacity of inter-zonal networks on the electricity price in separate zone is also evaluated.

1. DEVELOPMENT AND OPERATION PRINCIPLES OF ELECTRICITY MARKETS

Chapter 1 substantiates the topicality of the Doctoral Thesis by describing the course of development of electricity markets, analysing the advantages and disadvantages of various electricity trading models. This chapter is dedicated to various principles of electricity price determination in the conditions of market competition and limitations. The mechanism of determining area and nodal prices is compared. Individual attention is paid to the major deregulated electricity markets.

This chapter presents the analyses of the influence of limitations and electricity generation support on the electricity prices and regimes. Atually, all limitations are market-distorting factors. Limitations can be divided into technical and legal limitations. Technical limitations include both power system limitations (for example, limitations related to the network, generator capacity limitations, power unit shutdown limitations, reservoir limitations, etc.) and limitations of available energy resources, which may depend on the weather conditions (the sun, wind, air temperature, precipitation) or deliveries of energy resources (for example, the delivered amount of fuel, the produced biogas, etc.). Legal limitations include all the market-influencing factors that result from the legal framework. They comprise environmental limitations (for example, emission limitations, limitations regarding the minimum and maximum water level, etc.), requirements regarding energy efficiency (for example, savings of primary energy resources for high-efficiency combined heat and power plants), as well as support schemes for certain energy generation types or use of energy resources, which stimulate the development of that type of energy generation. Insufficient transmission capacity of power transmission lines leads to stricter technical limitations of the power network. This is a topical problem of the electrical transmission network in Latvia and on a global scale.

Topicalization of problems related to market-limiting factors has led to the definition of the goal of the Thesis and formulation of the solutions of the main task. This necessitated a search for solutions allowing full or partial elimination of the existing technical limitations of the electrical network in most operating modes. The Thesis discusses the impact of the transmission capacity of inter-area power transmission lines on the price of electricity in the area (the Baltic countries), considering the import possibilities and the support to energy generation from renewable energy resources or in combined heat and power generation. The formulation and algorithmization of the task are discussed in Chapter 2 [1]–[3].

2. FORMULATION AND ALGORITHMIZATION OF THE POWER SYSTEM MANAGEMENT AND OPTIMIZATION TASK

The goals of power system development and management and the peculiarities of the task

The management and development of power systems have the following four globally recognized [6] goals:

- increasing of efficiency;
- increasing of the reliability level;
- decreasing of the harmful environmental impact and climate change;
- ensuring of sustainability.

When making a decision, all four of the above goals need to be considered. This leads to the **first** important statement: power system management tasks belong to the class of multi-criteria tasks.

Multi-criteria tasks can be solved in various ways [4]. Let us only name the three most widely used solution approaches:

1. Choosing one criterion for formulating the objective function of the optimization task. The others are transferred to the class of limitations.
2. Formulating an integral objective function. In this case, all the criteria are united in the optimization objective function by using weight coefficients [5]. It is the choice of these coefficients that cause the greatest difficulty.
3. Determination of the Pareto compromise set [2], [6]–[7] and its presentation to the decision-makers. Further in the Thesis the first approach is used. Special attention is paid to the substantiation of the choice of values of limitations.

Optimization parameters

When solving the power system optimization tasks, it is necessary to choose many determining regime parameters for each hour of the planning period, for example, the active and reactive capacities of the generators, the voltage levels. These parameters need to be changed over time, adapting them to the energy demand and other influencing conditions. Apart from the abovementioned parameters, which are by their nature continuous quantities, in the power system management process it is possible to change its structure by switching equipment (generators, transformers, reactors) on or off. The switching on and off can be described by logical (Boolean) [7] variables, which can assume only two values: 0 or 1. As a result, the mathematical description of the task changes as well.

Even in the case of a small power system, considering that the variables may differ at various moments of time, it can be affirmed that it is necessary to perform a vast number of evaluations of structure operation possibilities. For example, in the case of thirty generators, when planning the regime for 168 hours (one week), the number of structures is $N = 5040$!

Considering the abovementioned, we can formulate the **second** statement: power system management tasks belong to the class of multi-parameter tasks with a large number of continuous and logical variables. The number of combinations of the values of logical variables is immense.

Indeterminate and random variables

The operation of power systems is significantly influenced by many factors, which are of stochastic (describable by a variable that can be described by a probability distribution function) or indeterminate (no information for substantiated choice of the distribution function) nature. The existence of such factors, on a large scale, is caused by the fact that the planning, management and optimization of regimes is in many cases done by considering the future situation. The future energy demand, water inflow, ambient air temperature, prices of energy carriers can be forecast only with limited accuracy. The **third** statement is as follows: <u>power system management tasks belong to the class of stochastic optimization tasks</u>.

Power system management as a game

Modern-day power systems operate in the conditions comprising many decision-makers, or players. Power plants are owned by various companies. The market is influenced by the decisions of energy traders. Consumers can consciously choose a regime that is advantageous for them.

The decisions of rivals can be disadvantageous for other players. Information about the decisions made is available only *post factum*. In some cases, it is possible for the players to unite – to build a coalition (a cooperative), exchange information, coordinate decisions and gain additional profit.

It is important to point out that in the description of the discussed situation, considering the actions and the influence of human beings, it is not possible to use the stochastic approach in its pure form. This leads to the **fourth** statement: <u>power system management takes place in the conditions which are considerably influenced by the actions of rivals and partners</u>.

The dimensionality, cross-correlation and self-correlation of influencing processes

As stated before, the considered task is influenced by many indeterminate or random (stochastic) parameters that are changeable over time. These changes can be described by using the methodology of stochastic processes [8]–[10]. It is important to point out that it is necessary to consider the tight links between the processes. For example: the link between ambient air temperature and loads in various nodes, water inflow in rivers or heat demand. In the description of processes, it is also necessary to consider the interrelation of the values of one process belonging to various moments of time.

This takes to the **fifth** statement: <u>the regimes of the power system are influenced by a multi-dimensional random process that is complexly linked within the time and space of variables.</u>

Decision-making at time intervals

When planning regimes, it is necessary to draw up a plan for the future; from the point of view of management flexibility, changes can be made to the drawn-up plans during implementation. Using of this possibility considerably influences the optimization task, making it more complicated. In this way, we can formulate the **sixth** statement: <u>power system management tasks belong to the class of multi-step tasks</u>.

Limitations

Two types of limitations are encountered in optimization tasks:

1) Limitations that can be described by equations (for example, limitations regarding the active and reactive power balance at nodes);
2) Limitations that can be described by inequalities (for example, power flow limitations in controlled sections, the power range of units or voltage limitations at nodes) [27]–[29].

"The curse of dimensionality"

The power system management optimization task can theoretically be solved by means of many known algorithms. Unfortunately, in practice it would require impossible resources both in terms of time and in terms of computer resources. Hence, the following sources of increase in the demand of computing resources can be singled out:

- A vast number of possible power system structures;
- Dimensionality of random processes and the need to consider cross-correlation and self-correlation;
- Non-linearity of the task at a large number of optimization variables;
- A large number of limitations and complexity of checking these.

Cases are possible when the checking of the fulfilment of limitations constitutes a separate, complex problem. Examples are limitations of the permissible power flows of high-voltage lines, the checking of which requires the simulation of operation of the whole system. Checking limitations on stability is even more complicated, since it is necessary not only to simulate the operation of the basic equipment but also the automatic control systems (controllers, relay-based protection devices, emergency control devices). The abovementioned issues are not addressed in the presented Thesis. It is assumed that system limitations can be checked by using industrial software for power system modelling, for example, ETAP or EUROSTAG [6].

Mathematical formulation of power system management optimization task

Let us assume that energy producers and consumers (further, we will call them all producers for brevity) have made an agreement and have founded an energy market. Let us allow for the possibility that every *i*-th of *K* electricity producers is planning its operation for a time period T_p, and they can choose their operating regime, which at every time moment *t* can be specified by the structure *S* of equipment used and by the parameters

$$X_{it}\left[X_{it1}, X_{it2}, \ldots, X_{itN_i}\right], \tag{2.1}$$

where N_i is the number of parameters chosen by the *i*-th producer. Let us assume that the production profit R_i is influenced by random quantities Π_t. Due to this influence, also the profit R_i is a random quantity. Assuming that for the random quantities Π_t the cumulative probability distribution function is known, the mathematical expectation of profit $M[R_i]$ can be expressed for the random quantity R_i:

$$M\left[R_i\right] = \int_0^{T_\mathrm{p}} \int_{-\infty}^{+\infty} \ldots \int \phi\left(X, S, \Pi\right) \mathrm{d}F_\Pi. \tag{2.2}$$

Equation (2.2) contains $X_{(-i)}$ and $S_{(-i)}$, which are part of X and S and depend on other decision-makers and are, in the general case, not known to the i-th participant of the market. In this way, in equation (2.2) there are two different sources of uncertainty and randomness: natural factors (temperature, precipitation, solar radiation etc.) and the actions of rivals.

Let us formulate the optimization task as follows:

$$\begin{cases} M\left[R_1\right] \Rightarrow \max, \\ \quad \vdots \qquad \vdots \\ M\left[R_N\right] \Rightarrow \max \end{cases} \tag{2.3}$$

subject to:

$$X, S, \Pi \in \Omega, \tag{2.4}$$

where Ω is the space of the allowed parameters and structures.

The formulated task cannot be solved without additional conditions since the interests of producers/consumers contradict. These additional conditions are introduced by accepting the market operating conditions. The most important role falls to the regulation of choosing bids that stipulates that in order to meet the energy demand, the cheapest bids are chosen. In the conditions of an energy market where the production capacities (the supply) exceed the demanded ones, task (2.3) can be divided into N independent maximization tasks as follows:

$$M\left[R_i\right] = \max \text{ for all } i, \tag{2.5}$$

since function φ used in (2.2) assumes the following form:

$$\phi\left(X, S, \Pi_t^*\right), \tag{2.6}$$

where Π_t^* is the set of random quantities, which, unlike Π_t, also contains market prices, which have to be forecast by the market participants.

Hence, the optimization task is greatly simplified, however it still remains too complicated for practical use since equation (2.2) contains a set Π of random numbers of large dimensionality, as well as the probability distribution function F_Π of corresponding dimensionality, a large number of possible structures S and a vast-dimensional integral.

Techniques of simplifying the optimization task

To solve a complicated optimization task, it is useful to simplify it. For this purpose, several techniques can be used:

1. Division of the planning time into intervals.

As the time is divided into intervals, in equation (2.2) the time integral is substituted by a sum and optimization variables are sought for each hour of the planning period. The algorithm used at the Nord Pool electricity exchange uses such substitution.

2. Replacement of the stochastic formulation of the task with a deterministic one.

The processes Π_t^* are substituted by their average values, and in equation (2.2) the multiple integral disappears. Hence, the probability distribution function F_Π is not necessary and the task is greatly simplified.

3. The scenario method.

It can be said that this is the method that has been developed, analyzed and used most widely [4], [11]–[13]. When using the scenario method, the random processes Π_t are substituted by their expected embodiments and the probability of each embodiment is evaluated. The use of the scenario method can be simplified by transforming the optimization task from the ensemble average to the time average [14]. This type of task formulation (see Fig. 2.1) enables us to considerably simplify the power plant operation planning task. The value of random variables can be found without explicit knowledge about the corresponding probability density function. However, in this case we need to perform forecasting processes, the duration of which exceeds the planning period T_p. The problem of the choice of planning period duration is discussed further.

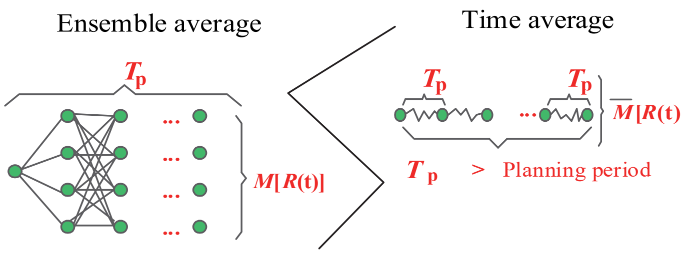


Fig. 2.1. Transformation of the optimization task from ensemble average to time average.

Methods of process forecasting

In recent years, artificial neural networks (ANNs) are widely used for forecasting the processes of power system management task [15]–[20]. Problems related to the choice of the ANN structure and its instruction have been addressed in many publications therefore they are not investigated in this Thesis. A model synthesized and checked by RTU researchers (R. Petričenko and K. Baltputnis) is used, which is capable of forecasting changes in the embodiments of processes over time [29]. The forecast is made by using the process recording results of the preceding days (45–60 days).

The structure of the forecasting model is shown in Fig. 2.2. It consists of an embodiment database (DB) and an artificial neural network (ANN). The databases that are used are available in electronic form via the Internet [16], [17].

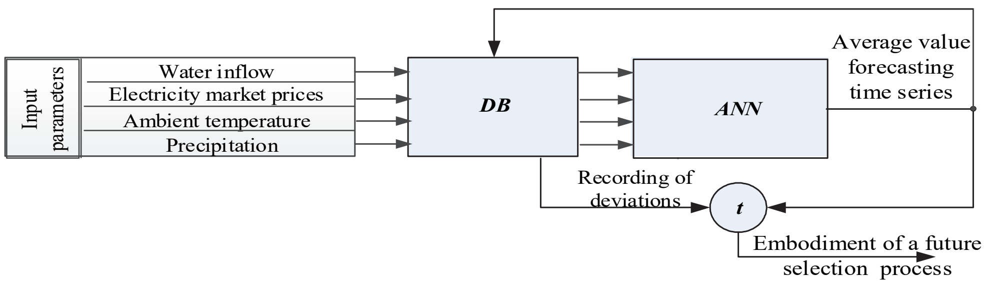


Fig. 2.2. Model for forecasting electricity price and water inflow.

Stages and procedures in solving the power system regime planning task

The planning of the power system regime is done stepwise as seen in Fig. 2.3.

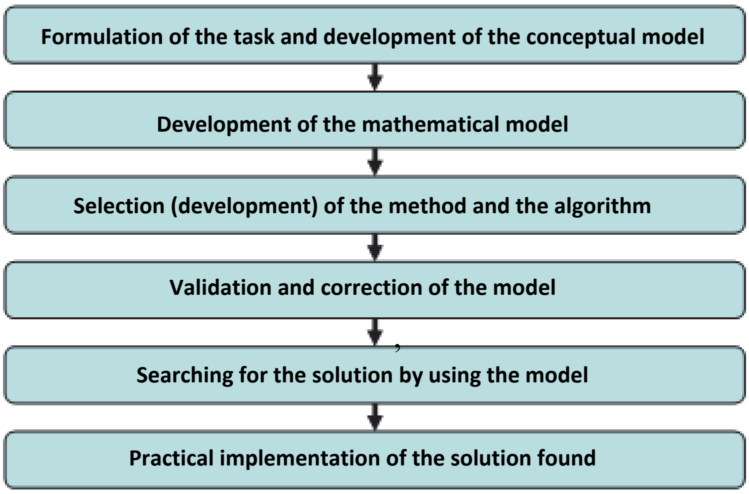


Fig. 2.3. The stages in the solution of the optimization task.

In order to find the solution of the task, certain mathematical programming methods have to be applied [21] depending on the objective function and the type and structure of the limitations.

From the analysis of methods used, it can be concluded that currently there is no single method for efficient solving of all optimization problems, thus the optimization methods that are best suited for the case under consideration are used. As an exception, linear programming is to be mentioned, for which a simplex method for solving the task has been developed. The method guarantees finding a global solution of the task, if there is one. This leads to the intention to use the simplex method also in the solution of non-linear programming tasks. This intention can also be implemented in practice by using **linearization techniques** and move from solving the non-linear programming task to solving an alternative linear programming task. Of course, a single linearization of the non-linear optimization task cannot lead us to the final solution. Still, by observing certain conditions, any initial non-linear optimization task can be substituted by sequential intermediary linear programming tasks, which are solved with the simplex method.

As a result of the aforementioned simplifications, it is possible to solve the optimization tasks in a stochastic and non-linear formulation for one plant. Attempts to do the same for a cascade of plants were unsuccessful since it was not possible to find the global maximum. The problem can be solved if decomposition of the task is used (Fig. 2.4). The above-discussed decomposition is based on the heuristic approach since the adopted possibility of linearization has been proved by means of numerical experiments.

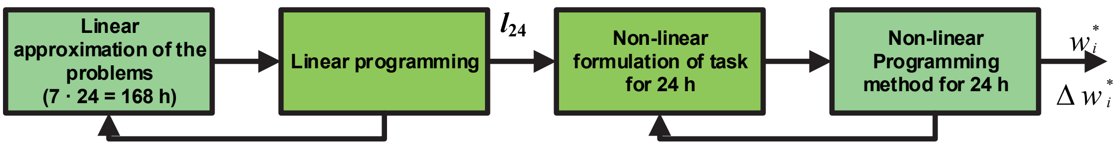


Fig. 2.4. Decomposition of the task.

3. OPTIMIZATION OF THE REGIMES OF BIOGAS POWER PLANTS, CONSIDERING MARKET PRICES AND LIMITATIONS

In Latvia, an outspoken upward tendency can be observed in the construction of new biogas and biomass plants. In accordance with the data of the Latvian Central Statistics Bureau, the capacity and the amount of produced energy of power plants using biogas are increasing year by year [22]. After the commissioning of new biogas power plants in 2016, there are currently sixty biogas power plants in Latvia with a total installed electrical capacity of 61.16 MW [23].

Small biomass and biogas power plants are built in the regions where the major part of local renewable energy resources is available, and they contribute to decentralized production of electricity. These electric energy sources are located near the place of electricity consumption and increase the reliability of power supply to consumers, diminish the losses in power transmission and distribution, diminish the energy costs and contribute to energy independence. Construction of this type of power plants is particularly advisable in regions where the capacity of the transmission lines is limited or there are some other limitations of the transmission capacity.

In Latvia, energy production from biogas is encouraged by means of the mandatory procurement of electricity, which prescribes the purchase of the produced electricity at a guaranteed purchase price, which is considerably higher than the electricity market price (the feed-in tariff). The mandatory procurement in the case of limited primary resources is in contradiction with the stimulation of generation at the peak (maximum price) hours of energy demand (see Fig. 3.1).

The goal of the author is in this chapter to develop an algorithm for managing the regimes of combined heat and power plants fueled by biogas by using the stochastic approach and considering the limited available resources for biogas production and the need to ensure the demanded amount of heat, as well as to substantiate the need to use such an algorithm as the power plant operates in market conditions.

Using the forecast of electricity price and heating demand with the proposed complex algorithm for optimization problem solving, optimal biogas resource allocation can be obtained.

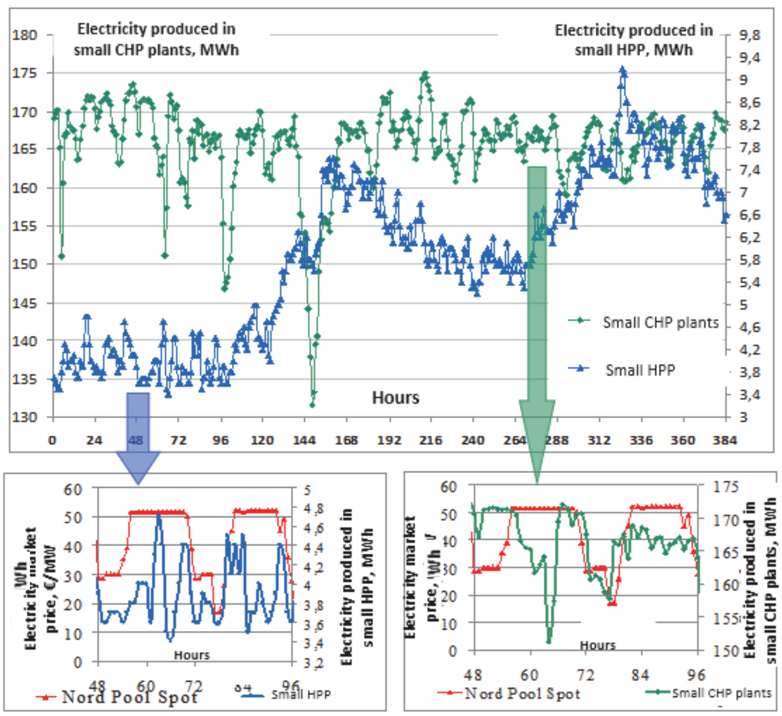


Fig. 3.1. Examples of power generation in plants.

The possible solution can also be used for reconsidering the present support scheme, by providing possibilities of adapting the management of the generation equipment and the cooperation of power plants and the public trader to the market conditions [24].

Starting cooperation (hereinafter, "coalition") enables the public trader and the power plants to obtain additional income from the adaptation of the schedule of its operation to the electricity market price schedule and at the same time poses the task of distributing that income among the participants of the coalition. The Thesis offers a solution to this problem by using the cooperative game theory (Shapley value).

The additional income obtained by the public trader can be used for the reduction of the burden of support costs on energy consumers. Therefore, we can conclude that the cooperation between the public trader and the power plant operator, which has limited primary resources, provides an additional income for both parties and allows to reduce the renewable resources support burden on energy consumers. Using the Shapley value for distributing the additional income between the power plant and the public trader was previously discussed using the example of small hydropower plants [7].

Formulation of the optimization task

In our case, we initially use the forecasting of random processes for a time period of 168 hours, which reflects the time average approach; after that, we determine the maximum income by using the forecast of electricity prices and heat demand. The structure of the optimization procedure is shown in Fig. 3.2.

In order to forecast the heat demand and electricity market prices, ANN are used [24] (10 electricity price forecasts and 10 heat load schedules have been used).

After the harmonization of the supply and demand bids submitted by the market participants, the hourly electricity prices c_i and the heat demand are known. This means that we can perform the optimization by using linear programming, provided that the characteristics of costs are constant over the considered time period.

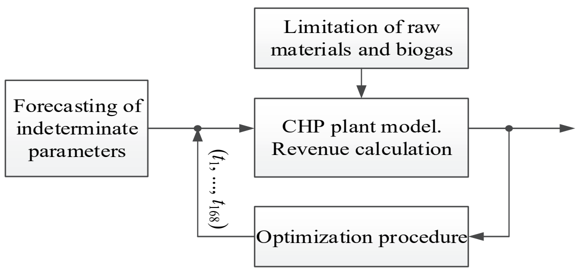


Fig. 3.2. Optimization procedure.

By using the obtained forecasts, we can formulate the optimization task of the biogas combined heat and power plant operation in the conditions of limited biogas resources:

$$R_t\left(W^*_{\mathrm{el}\,i}; W^*_{\mathrm{th}\,i}\right) = \left\{ \begin{array}{c} \arg\max \sum_{i=1}^{T_\mathrm{p}} \left(W_{\mathrm{el}\,i}\left(l_i\right) \cdot c_i + W_{\mathrm{th}\,i}\left(l_i\right) \cdot c_{\mathrm{th}} - C\left(l_i\right) \right) \\ i \in \tau;\ \tau = \left\{1, \ldots, T_\mathrm{p}\right\} \\ W_{\mathrm{el\,min}} \le W_{\mathrm{el}\,i} \le W_{\mathrm{el\,max}} \\ W_{\mathrm{th\,min}} \le W_{\mathrm{th}\,i} \le W_{\mathrm{th\,max}} \\ \sum_{i \in T} l_i \le L_T \end{array} \right\}, \quad (3.1)$$

where c_i the hourly electricity price, EUR/MWh;

c_{th} the fixed heat price, EUR/MWh;

$W_{el\,i}$, $W_{th\,i}$ the amount of generated electricity and heat $\left(\{W_{el\,i}; W_{th\,i}\} \in R_i;\ i \in \tau\right)$, MWh;

$W^*_{el\,i}, W^*_{th\,i}$ the amount of generated electricity and heat, MWh

$W_{el\,min}$, $W_{el\,max}$, $W_{th\,min}$, $W_{th\,max}$ minimum and maximum possible values of electricity and heat, considering the technical limitations, MWh;

$C(l_i)$ the costs of raw materials, EUR/t.

From the mathematical point of view, the hourly rate of generated electricity is the most important variable for making a decision when solving the investment calculation problem and planning the operation.

The structure of the biogas power plant optimization algorithm is provided in Fig. 3.3. Using the electricity price and heat demand forecast and this complex algorithm in solving the optimization problem, we can find the optimum distribution of biogas resources.

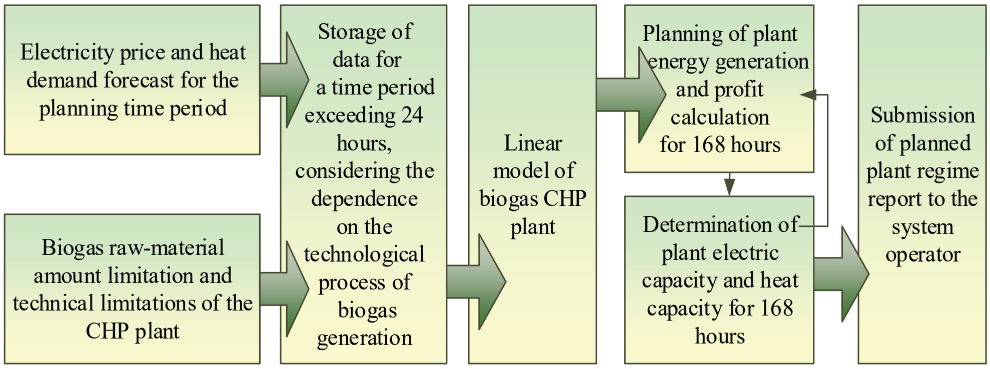


Fig. 3.3. The algorithm of the optimization process of biogas combined heat and power plant operation.

Since the coalition does not require the abolishing of valid normative acts for the support of renewable energy sources, the task can be formulated in two ways: by considering the fixed purchase price or the electricity market prices in the optimization process. The idea of the approach is as follows:

1. If the power plant operates without a trader and makes use of the granted support, its operation can be optimized by striving to generate the maximum amount of energy without regard of the peak demand hours (the hours when the electricity price on the market is at its highest). Let us assume that in this case the received revenue is I_1. Part of this revenue, I_{t1}, is received from the public trader, which sells the electricity generated by the power plant on the market whereas the remaining part, I_{s1}, is received from the community according to the support scheme:

$$I_1 = I_{t1} + I_{s1}. \tag{3.2}$$

2. If the power plant operates as an independent market participant according to market conditions that are advantageous to society, a total revenue I_2 can be received with a market component I_{t2} and support I_{s2}. Support I_{s2} will be smaller than the support I_{s1} since the optimization is performed by maximizing I_{t2}, which is larger than I_{t1}, yet diminishes the amount of energy generated. As a result, such operation may prove less advantageous than the previously described model since I_1 is larger than I_2 and such an operation will not be chosen.

3. However, if the plant operates in coalition with the trader, and the power plant operates according to the algorithm described in Item 2, their total additional profit I_p to be distributed is as follows:

$$I_p = (I_{t2} - I_{t1}) - (I_1 - I_2), \quad (3.3)$$

since the trader receives a larger revenue from selling electricity on the market at higher prices whereas the total revenue of the producer diminishes.

An example of biogas power plant optimization

The considered optimization task is based on the example of a biogas power plant in Latvia. Chicken manure is used as the primary energy resource. To create an optimization model, it is important to know the possible amount of biogas production. The heat and electricity generation equation depends on the amount of gas used, the efficiency of the plant and the calorific value.

In the Thesis, we take into account that the total amount of the generated heat and electricity depends on the amount of raw materials filled into the fermenters for the planning time period. Given the amount of the chicken manure, the potential amount and calorific value of the biogas, we can, according to (3.1), calculate the optimal amount of heat and energy that is to be produced, taking into account the electricity market price and the fixed heat price. The task is solved by using the linear programming simplex method.

When planning the regime, it has to be taken into account that there may be a determined minimum amount of heat to be generated by the combined heat and power plant, which is required to ensure the production process. In order to clearly demonstrate the influence of the raw material amount limitation on the result, let us look at two cases when 1050 t and 882 t of chicken manure is available.

The obtained results are presented in Table 3.1. At the time periods when the electricity price is at its highest, the combined heat and power plant produces the maximum amount of electricity and heat. On the other hand, when the electricity price is low, a large amount of biogas remains unused and the amount of produced electricity is proportional to the minimal required heat production amount. The results of the optimization show that adaptation of the energy production schedule to the electricity market price ensures a higher profit than in the case of a uniform distribution of biogas.

In addition, the stricter the raw materials limitation, the larger is the additional gain that can result when choosing the optimization of energy generation schedule according to market price. Hence, it can be concluded that it is advisable to use biogas in accordance with the proposed stochastic optimization algorithm.

Table 3.1

The results of the biogas combined heat and power plant optimization task [25]

Available amount of chicken manure, t	Biogas utilization distribution approach	Profit, EUR	Profit difference depending on the approach used, EUR (%)
1050	Uniform distribution of biogas over the whole planning period	17 905.20	998,54 (5,6 %)
	Distribution according to the electricity market price	18 903.74	
882	Uniform distribution of biogas over the whole planning period	15 040.37	965,53 (6,4 %)
	Distribution according to the electricity market price	16 005.89	

The obtained results prove that cooperation between public trader and power plant operator makes it possible to alleviate the support-induced burden for the electricity users and/or provide additional income to both sides. It has to be pointed out that changing of the support scheme would influence the choice of equipment of the biogas plant already in the designing stage, contribute to increasing the capacity and its use at the peak hours of energy demand.

4. OPTIMIZATION OF THE OPERATING REGIME OF HYDROPOWER PLANTS CONSIDERING MARKET PRICES AND LIMITATIONS

4.1. Development Stages and Problems of Hydropower Plants

The development of a hydropower plant (HPP) consists of three main stages.

1. Project formulation, planning and analysis as to advantageousness. This stage takes place before the implementation stage; here, it is necessary to draw up a report (a project sketch) comprising all investigation, data collection, feasibility studies, risks analysis and cost-benefit analysis. This stage is important for both the project initiators and the potential creditors.

2. Project implementation. Based on the feasibility study, a decision is made to move further to project implementation after choosing the best alternative. The work has to be started with planning and data collection. Evaluation of hydropower resources requires several types of data, including detailed information about water bodies, river geometry, topography and available water amount. These data allow evaluating variables that are of crucial importance to hydropower production: net head, design flow rate and the number and capacity of turbines [14].

3. Operation of the power plant. Taking into account that the owners of the plant strive to maximize their profit it is necessary to set up a regime management system.

Methodologies for implementing all of the aforementioned steps have been created and software is available, based on the deterministic approach, which results in unsuitability for new conditions of the energy market. Utilization of the energy resources of small rivers is stimulated by introducing support schemes [24], [26], [29], [30]. The design imperfection of these schemes leads to incorrect use of hydropower resources from the point of view of society since, when supporting renewable energy resources, a fixed energy price is determined and the producer strives to maximize the amount of generated energy, ignoring the increased demand for it during the peak hours.

On one river there can be a number of plants that belong to different owners. Another question arises: how to coordinate the operation of these plants in the way to obtain the maximum summary profit, and how to distribute this profit fairly. The existing methodologies have ignored this problem. This chapter describes a methodology, which eliminates the abovementioned shortcoming.

Two types of facilities are discussed: small and large hydropower plants. The optimization task for the first type of facilities is simpler since the power plants of this type mostly contain only one or two turbines. Even in the case of a cascade of plants, the number of combinations of turbines in operation is small. Whereas, in the case of large power plants, for example, the Daugava HPPs, the number of turbines may reach tens; this, considering the duration of the planning period, makes it necessary to analyze a vast number of combinations of units in operation.

Besides, intensive construction of small HPPs is taking place worldwide, which determines the importance of improving the methods for studying the feasibility of this type of facilities. Whereas, the construction of large HPPs has nearly stopped. Yet regime planning and management for large HPPs retain their importance.

In this chapter, the main attention is devoted to the optimization algorithm and software, which is the result of a study titled "Development of Software for JSC 'Latvenergo' Power Plant Regime Planning", which has been in progress for three years, involving more than ten researchers. The idea to use the linear and non-linear formulations of the task together belongs to the author of the present Thesis. This idea made it possible to diminish the calculation time a number of times. R. Petričenko and K.Baltputnis, using the algorithm developed by the author and R. Varfolomejeva, have synthesized a user-friendly software product. The approbation of individual blocks of the developed algorithm was done on the basis of simplified examples, which have been published in [14], [27] and have been repeated in the appendices of the present Thesis.

The problems related to the design and management of small HPPs have been thoroughly reflected in author's publications, which are included in the appendices of the Thesis.

4.2. Operation Optimization Algorithm of a Cascade of Hydropower Plants

The operation of three hydropower plants is analysed. The expected profit of the cascade of power plants, P_R, can be described by a non-linear function, which has to be maximized:

$$P_R(t) = \sum_{k=1}^{K} c_k \sum_{l=1}^{L} P_{lk} = F\left(c_k, W_{rk}, V_{lk}\right), \quad \forall k \in K, \forall l \in L \tag{4.1}$$

Subject to:

$$\underline{P_l} \le P_{lk} \le \overline{P_l}, \tag{4.2}$$

$$\underline{h_r} \le h_{rk}\left(P_{lk}\right) \le \overline{h_r}, \ \forall r \in R, \tag{4.3}$$

$$\underline{\mathrm{d}h_{rk}} \le \mathrm{d}h_{rk}\left(P_{lk}\right) \le \overline{\mathrm{d}h_{rk}}, \tag{4.4}$$

$$h_{rk} = H_r, \tag{4.5}$$

where

$K, L, R; h, l, r$ the sets of the hourly data registration periods of the hydropower units and reservoirs;

P_{lk} the amount of electricity generated by hydropower unit l over hour k (a decision variable);

c_k electricity price at hour k;

$\underline{P_l}, \overline{P_l}$ limitations on the capacity of the units (the minimum and the maximum);

$h_{rk}\left(P_{lk}\right)$ water level in reservoir r at hour k;

$\underline{h_r}, \overline{h_r}$ limitations on the water level in reservoir r (the minimum and the maximum);

$\mathrm{d}h_{rk}\left(P_{lk}\right)$ lowering/rise of water level in reservoir r over hour k;

$\overline{\mathrm{d}h_{rk}}$, $\underline{\mathrm{d}h_{rk}}$ limitations on the rise/lowering of water level at hour k (minimum and maximum);

W_{rk} water inflow to the reservoir over hour k;

h_{rk} water level at the end of the planning period;

V_{lk} water flow through unit l over hour k.

The solution of the task (4.1) is related with the following peculiarities:

1. Functions $h(P)$ and $\mathrm{d}h(P)$ are obviously non-linear, especially in the case of relatively small reservoirs. The amount of energy generated by power plants is in non-linear dependence on the flow rate through the turbines, the water inflow and the net hydraulic head of the reservoirs. Due to the complicated geometry, the water level in reservoirs depends on non-linearity of the inflow. Additionally, it has to be taken into account that the same amount of electricity can be produced at a power plant by using various combinations of units in operation.

2. Status variables c_k and W_{rk} can be forecast with a limited accuracy and they are to be regarded as stochastic quantities. The changes in these quantities over time can be described by stochastic functions.

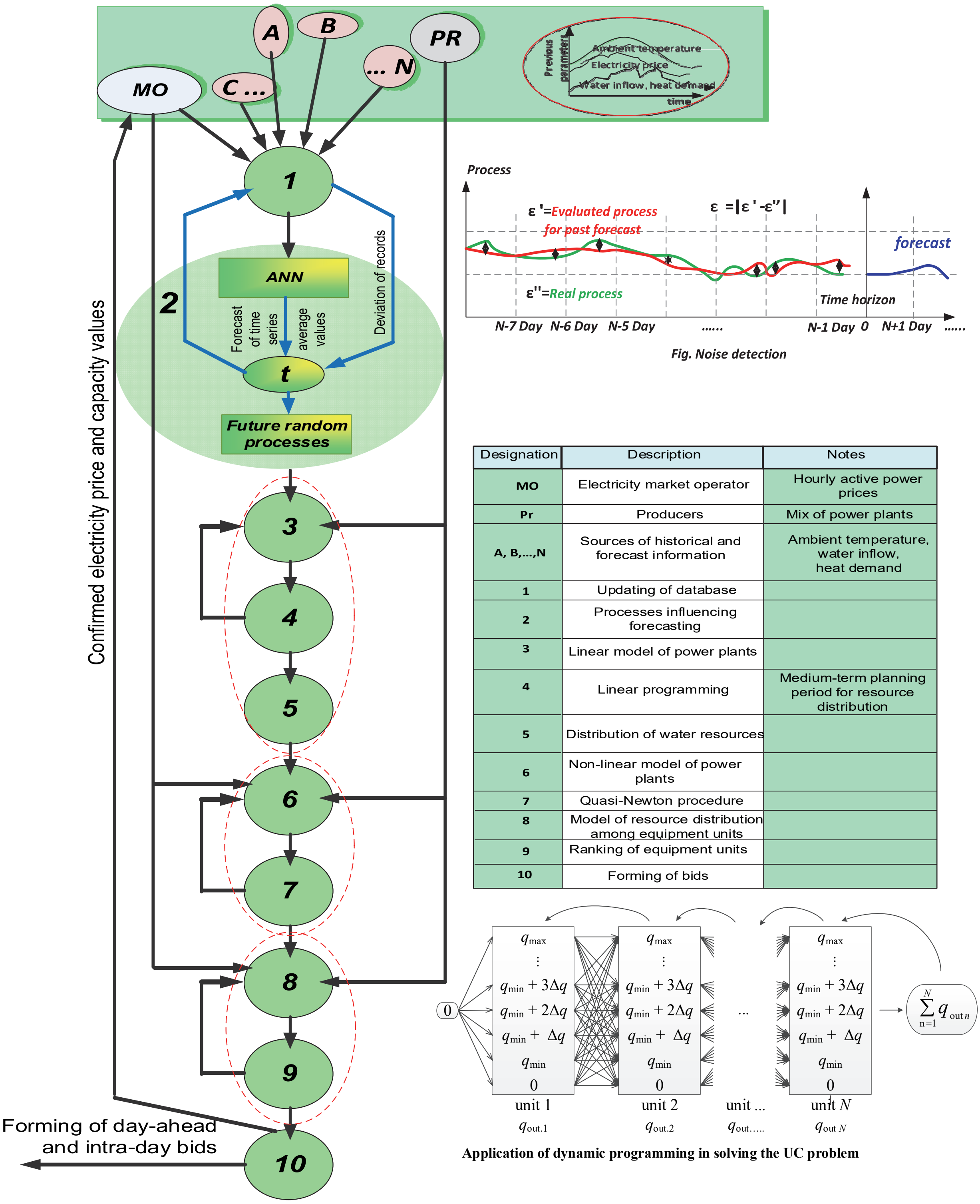
In order to overcome the difficulties brought about by these peculiarities, it is necessary to change the mathematical formulation of the optimization task. The market price and the water inflow are the main indeterminate parameters that influence the operation of the discussed hydropower plants. These parameters can be forecast only with a considerable level of deviation.

The sequence of actions required to solve the task is reflected in the structure of the evaluated algorithm shown in Fig. 4.1. The following techniques have been used: linearization, diminishing of the number of variables, diminishing of the duration of the planning period and return to the deterministic task formulation.

Within the first block of the HPP cascade optimization algorithm, the limiting environmental and technological parameters for the HPP are determined and database is updated.

Within the second block the indeterminate parameters are forecast, i.e. the electricity market price and the water inflow for the planning period. The forecast of price and water inflow takes into account historical data of the previous two weeks, including the deviation of the actual value from the forecast for the previous day.

The optimization process starts after the forecasting. The optimization is done in two stages. In the first stage of the optimization process (Fig. 4.1, Block 3–5), a linear model is formed, within which the planning of the production and the profit gained by the HPP cascade for a longer planning period is done (7 days). Using of the linear model makes it possible to save the calculation time. The obtained results are determined more precisely in the second stage of the optimization process (Fig. 4.1, Block 6–7), when a non-linear model is used and optimization of the operation of the HPP cascade (the production schedule and the forecasted profit gained) for a shorter time period is done (24 hours). As a result, the active power of the HPPs for every hour of the 24-hour period is determined.



Designation	Description	Notes
MO	Electricity market operator	Hourly active power prices
Pr	Producers	Mix of power plants
A, B,...,N	Sources of historical and forecast information	Ambient temperature, water inflow, heat demand
1	Updating of database	
2	Processes influencing forecasting	
3	Linear model of power plants	
4	Linear programming	Medium-term planning period for resource distribution
5	Distribution of water resources	
6	Non-linear model of power plants	
7	Quasi-Newton procedure	
8	Model of resource distribution among equipment units	
9	Ranking of equipment units	
10	Forming of bids	

Fig. 4.1. Algorithm of optimization of HPP operation planning.

In the last stage (Fig. 4.1, Block 8–9), unit power for each unit in each HPP is selected using dynamic programming (DP). Block 10 envisages the formation of a price bid for the day ahead.

On the basis of this algorithm, specialized software OPTIBIDUS has been developed for planning the operation of a HPP cascade.

4.3. Examples of HPP Cascade Operating Regime Optimization

Further, the most interesting results of the conducted experimental calculations are presented.

Checking of the feasibility of limitations

One of the limitations the fulfilment of which is strictly controlled, is the allowable reservoir level description of inequalities. If it is assumed that the plant can diminish the water level in its reservoir by one metre together with the water inflow, the plant can gain a larger profit value than in the case when only discharging the water inflow. For example, at Pļaviņas HPP, the water level in the beginning of the optimization period is 35 m, which can be diminished to 34 m at the end of the optimization period; at Ķegums HPP – 23 m and 22 m, respectively; at Riga HPP – 11.8 m and 10.8 m, respectively.

The obtained results – changes in the water level and production at Daugava HPPs, are shown in Fig. 4.2 and Fig. 4.5. From the changes in the water level schedule it can be seen, that the set condition is completely satisfactory.

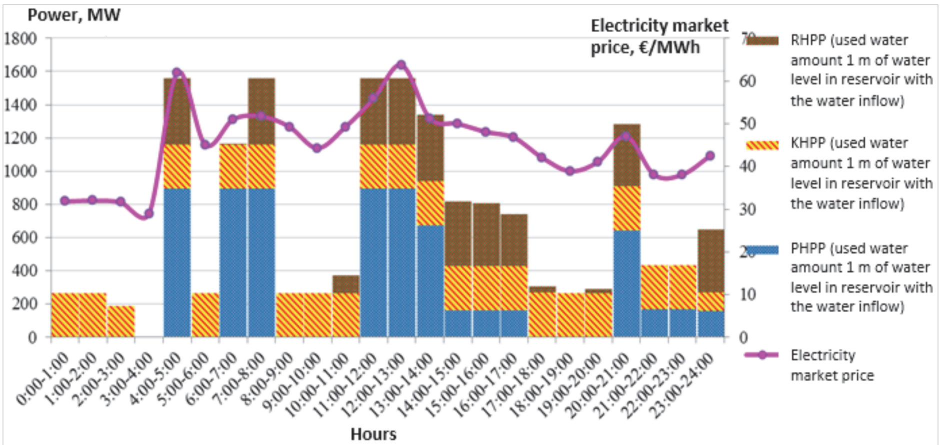


Fig. 4.2. Calculation of active power of Daugava HPPs in non-linear task formulation.

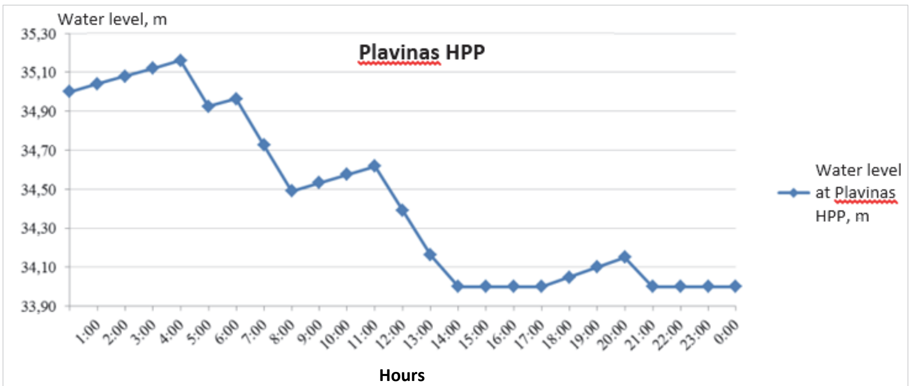


Fig. 4.3. Changes in water level in the water reservoir of Pļaviņas HPP.

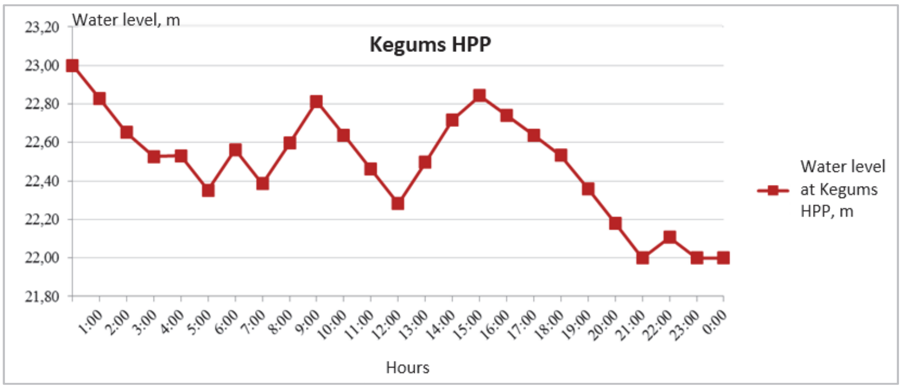


Fig. 4.4. Changes in water level in the water reservoir of Ķegums HPP.

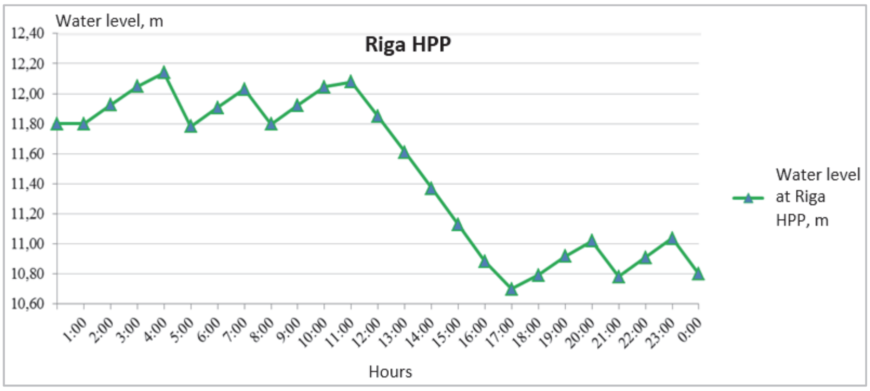


Fig. 4.5. Changes in water level in the water reservoir of Riga HPP.

Groundedness of limiting the planning period up to 168 hours

Fig. 4.6 shows the results of solving the water resource distribution task, limiting the planning period to 2, 3, …, 7 days. The analysis of the results makes it possible to conclude that further increasing of the planning period may only provide an insignificant effect since we still have to use the water level value of the end of the first day.

a)

b)

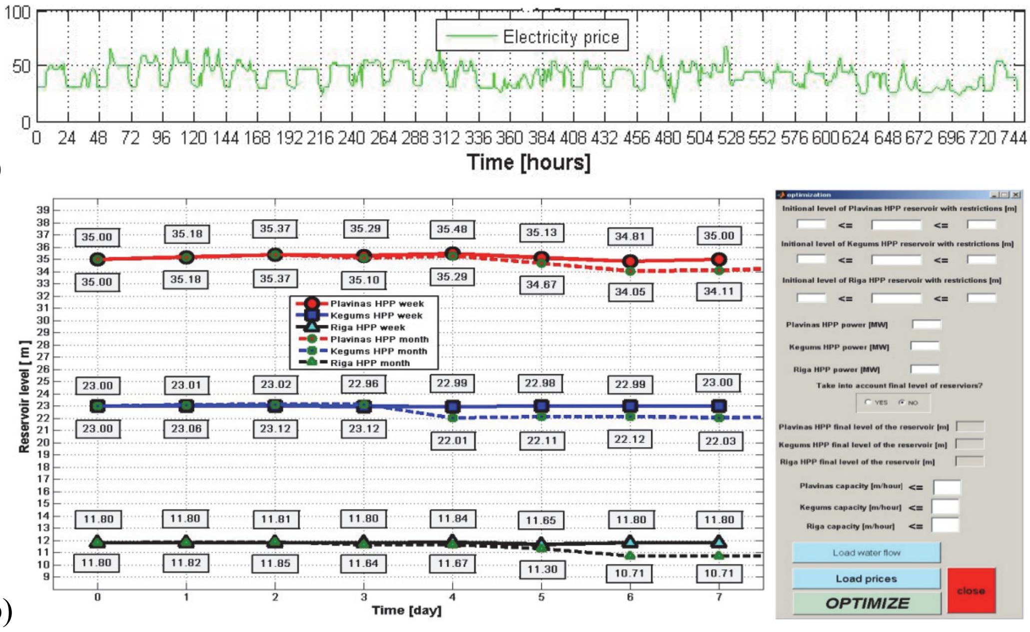


Fig. 4.6. Water level in the water reservoirs of the Daugava HPPs at changing durations of the forecasting period: a) forecast of the electricity market price for one month (744 hours); b) water level in the water reservoirs as a result of the optimization performed a week ahead and a month ahead.

The obtained results make it possible to conclude that the proposed model can be used as the basis when developing software for the optimization of the Daugava HPP cascade. For verification of the optimization procedures, a large number of numerical experiments have been carried out. The results allow a conclusion about the plausibility of the experiments and compliance with the limitations as well as about the ability of the procedure to find the global profit maximum.

5. THE RESULTS OF THE CHECK OF THE OPTIMIZATION PROCEDURES, CONSIDERING THE NETWORK LIMITATIONS

This chapter describes algorithms and procedures, which, unlike the ones discussed above, have not yet been implemented in the form of industrially usable software.

An algorithm is proposed for solving the optimization task for system and determining the nodal prices, taking into account the impact of electricity networks and electricity prices of locally situated (in zone or node) producers, in linear and non-linear statement. It is proposed to use the reduced gradient method and Lagrange's method of indeterminate multipliers for solving of the mentioned non-linear tasks.

The approbation of the proposed system optimisation and nodal price calculation algorithm has been done using the example of the Baltic power system (see Fig. 5.1.). The results of experimental calculations have confirmed the possibility of using the proposed algorithm. In the discussed example, we used assumptions regarding generation price bids, which do not correspond to actual facts since these data cannot be obtained officially. Using real-life data would make it possible to obtain the actual electricity prices at specific nodes (countries).

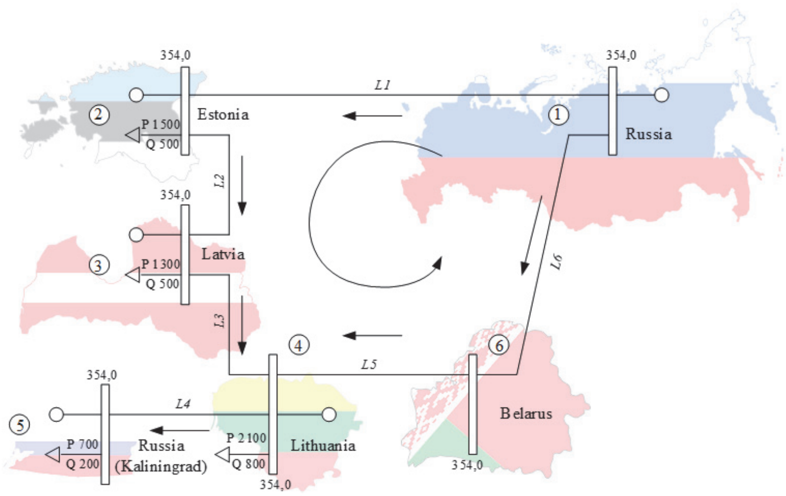


Fig. 4.6. Simplified principal scheme of the Baltic Power System.

The obtained results indicate that consideration of inhomogeneity in calculations does not extend the calculation time and the result is not significantly affected. Limitations equally have significant impact on power system regimes in both homogeneous and inhomogeneous network case. However, in the case of the replacement of the inhomogeneous networks with homogeneous model the validation of this model is required. It is a separate issue and is not addressed in this Tesis.

Influence of inter-zonal transmission lines on electricity price in a zone

The influence of the transmission capacity of inter-zonal power transmission lines on electricity price in an individual zone (a generalized node) in market conditions is evaluated in Thesis. In order to reflect the peculiarities of operation of the Latvian power system, the possibilities of import from the neighbouring zone with a lower price bid as well as mandatory procurement of electricity generated from renewable energy resources are taken into account.

The simplified power system, which is substituted by a generalized node, is used (Fig. 5.1).

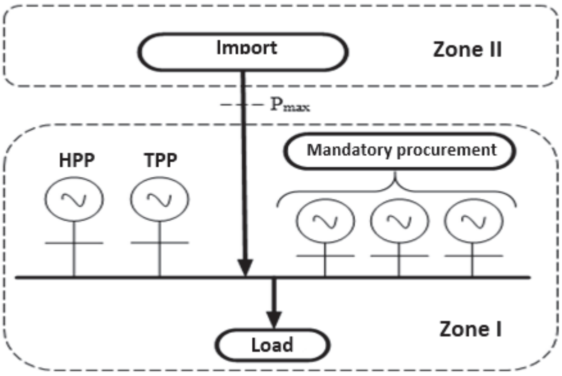


Fig. 5.1. Power system.

The technological limitations regarding the minimum and maximum capacity of plants and price bids (assumed to be constant over time) are summarized in Table 5.1.

Table 5.1

Technological limitations regarding capacity of plants and price bids

	TPP	HPP
P_{min}, MW	170	65
P_{max}, MW	662	402
c, EUR/MW	46	35

A forecast of the changes in the total load is shown in Fig. 5.2. It is assumed that the power losses constitute 5 % of the load. The optimization is performed by dividing the day into 24 one-hour periods.

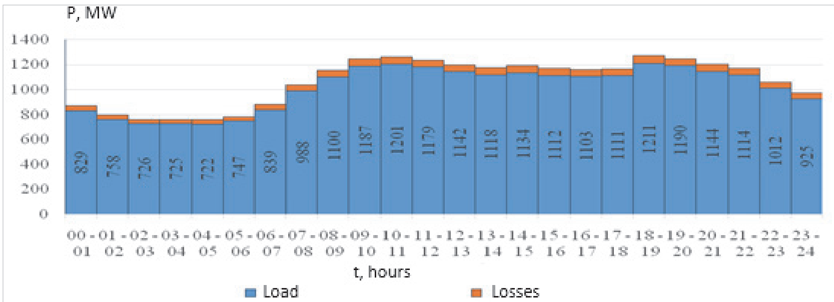


Fig. 5.2. Load forecast in Zone I

It is assumed that the existing water amount can ensure the operation of the HPP with maximum capacity over the discussed time period. Additionally, we have taken into account the limitation regarding the regulation of the capacity of a thermal power plant (TPP) over time (MW/min), which prescribes that the capacity of the plant must not change by more than 180 MW/h.

The proposed import price from Zone II and a forecast of the amount to be purchased within the mandatory procurement at a fixed price, c_{OI} = 96 EUR/MW, are provided in Fig. 5.3.

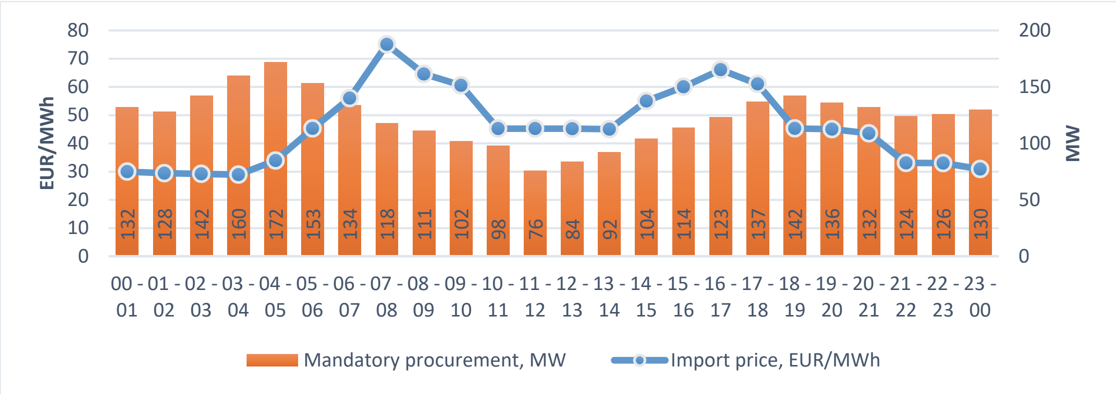


Fig. 5.3. Behaviour of import prices and the amount of mandatory procurement.

In order to evaluate the influence of the transmission capacity of inter-zonal power transmission lines, let us look at various scenarios of limitations of the maximum of transmission capacity – from 0 MW to 700 MW and unlimited flow volume.

In addition, we take into account the power balance in the system:

$$s^t_{\mathrm{TES}}P^t_{\mathrm{TES}} + s^t_{\mathrm{HES}}P^t_{\mathrm{HES}} + P^t_{\mathrm{OI}} + s^t_{\mathrm{imp}}P^t_{\mathrm{imp}} = P^t_{\mathrm{SI}} + \Delta P^t_{\mathrm{SI}},, \quad (5.1)$$

where

$s^t_{\mathrm{TES}}P^t_{\mathrm{TES}}$ the power produced by TPP at hour t, MW;

$s^t_{\mathrm{HES}}P^t_{\mathrm{HES}}$ the power produced by e HPP at hour t, MW;

P^t_{OI} the power produced within the mandatory procurement at hour t, MW;

$s^t_{\mathrm{imp}}P^t_{\mathrm{imp}}$ the import power used at hour t, MW;

P^t_{SI} the summary system load at hour t, MW;

ΔP^t_{SI} the summary power losses in the system at hour t, MW.

The objective function of the task is as follows:

$$F = \min\left[\sum_{t=1}^{n}\left(s^t_{\mathrm{TES}}P^t_{\mathrm{TES}}c_{\mathrm{TES}} + s^t_{\mathrm{HES}}P^t_{\mathrm{HES}}c_{\mathrm{HES}} + P^t_{\mathrm{OI}}c_{\mathrm{OI}} + s^t_{\mathrm{imp}}P^t_{\mathrm{imp}}c_{\mathrm{imp}}\right)\right],. \quad (5.2)$$

where

$s^t_{\mathrm{TES}}P^t_{\mathrm{TES}}$ the power produced by the TPP at hour t, MW;

$s^t_{\mathrm{HES}}P^t_{\mathrm{HES}}$ the power produced by the HPP at hour t, MW;

P^t_{OI} the power produced within the mandatory procurement at hour t, MW;

$s^t_{\mathrm{imp}}P^t_{\mathrm{imp}}$ the import power used at hour t, MW.

The optimization task was solved by using the generalized reduced gradient method. The optimization was done by using a computer with Intel® Core™ i5-2430M CPU @ 2.40

GHz, 4 GB RAM. The results of power distribution are shown in Fig. 5.4. to Fig. 5.7. Depending on the limitations scenario, the calculation time for various scenarios ranged from 13.884 seconds to 109.091 seconds [28].

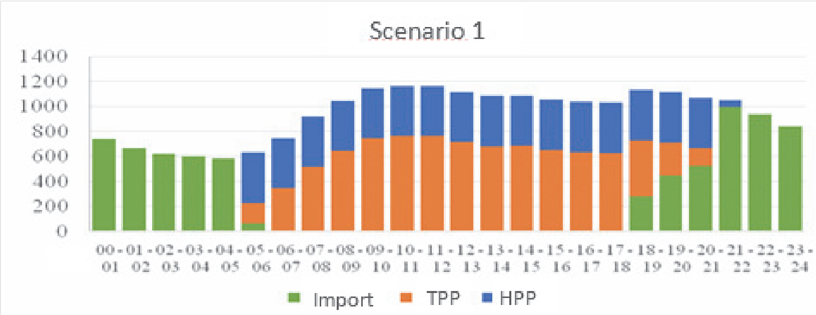


Fig. 5.4. Load distribution among power plants and import without limitation on inter-zonal power flow.

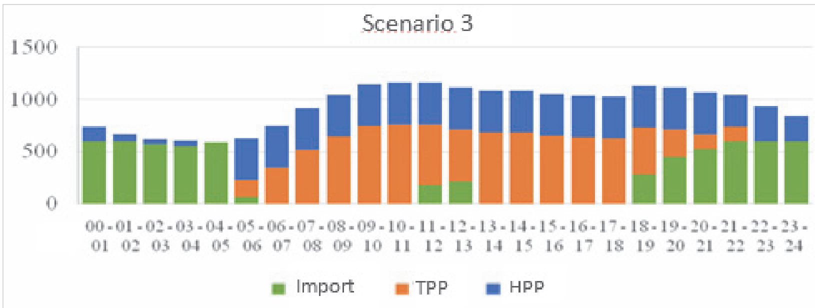


Fig. 5.5. Load distribution among power plants and import with 600 MW limitation on inter-zonal power flow.

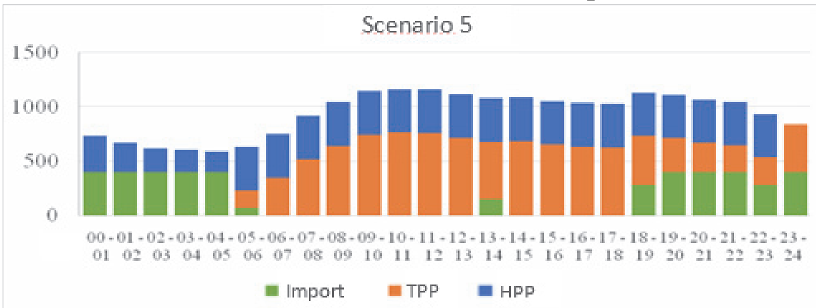


Fig. 5.6. Load distribution among power plants and import with 400 MW limitation on inter-zonal power flow.

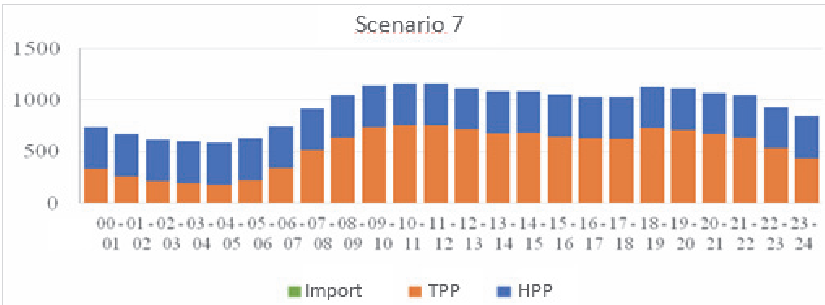


Fig. 5.5. Load distribution among power plants and without import (with 0 MW limitation on inter-zonal power flow).

The results of the electricity market price in Zone I are shown in Table 5.5. The obtained results make it possible to conclude that absence of limitations enables optimal distribution of load among power plants and import. Thus, in Scenario 1, the best result is achieved, which enables power plants to abstain from participation in the market if the electricity market price is lower than the prime cost.

Table 5.4

The behaviour of market price in zone I

Time	Scenario						
	1	2	3	4	5	6	7
0:00–1:00	30.01	35.00	35.00	35.00	35.00	46.00	46.00
1:00–2:00	29.46	29.46	35.00	35.00	35.00	35.00	46.00
2:00–3:00	29.21	29.21	35.00	35.00	35.00	35.00	46.00
3:00–4:00	28.95	28.95	35.00	35.00	35.00	35.00	46.00
4:00–5:00	33,94	33.94	33.94	35.00	35.00	46.00	46.00
5:00–6:00	46.00	46.00	46.00	46.00	46.00	46.00	46.00
6:00–7:00	46.00	46.00	46.00	46.00	46.00	56.03	46.00
7:00–8–00	75.05	75.05	75.05	75.05	75.05	75.05	46.00
8:00–9:00	64.59	64.59	64.59	64.59	64.59	64.59	46.00
9:00–10:00	60.57	60.57	46.00	60.57	60.57	60.57	46.00
10:00–11:00	46.00	46.00	46.00	46.00	46.00	46.00	46.00
11:00–12:00	46.00	46.00	46.00	46.00	46.00	46.00	46.00
12:00–13:00	46.00	46.00	46.00	46.00	46.00	46.00	46.00
13:00–14:00	46.00	46.00	46.00	46.00	46.00	46.00	46.00
14:00–15:00	55.01	55.01	55.01	55.01	55.01	55.01	46.00
15:00–16:00	60.01	60.01	60.01	60.01	60.01	60.01	46.00
16:00–17:00	66.08	66.08	66.08	66.08	66.08	66.08	46.00
17:00–18:00	61.03	61.03	61.03	61.03	61.03	61.03	46.00
18:00–19:00	46.00	46.00	46.00	46.00	46.00	46.00	46.00
19:00–20:00	46.00	46.00	46.00	46.00	46.00	46.00	46.00
20:00–21:00	46.00	43.57	46.00	46.00	46.00	46.00	46.00
21:00–22:00	35.00	35.00	46.00	46.00	46.00	46.00	46.00
22:00–23:00	33.02	35.00	35.00	46.00	46.00	46.00	46.00
23:00–24:00	30.91	35.00	35.00	35.00	46.00	46.00	46.00

The results of the objective function for various scenarios are shown in Table 5.5. As the limitations are aggravated (along with the diminishing of the transmission capacity of the lines), the value of the objective function and the electricity market price in Zone I increase.

Table 5.5

Value of the objective function of the task of power system regime optimization

Scenario Nr.	*F*, EUR
1	1 262 435.3
2	1 265 123.5
3	1 267 738.9
4	1 272 349.4
5	1 281 582.4
6	1 294 551.9
7	1 317 863.1

The solution of this task proves the possibility of using the developed algorithm also in solving the dynamic formulation of the power system optimization task over time.

In practice, in real-life power systems with inhomogeneous networks, the optimization task becomes considerably more complicated since the matrices of current distribution ratios have a complex form.

CONCLUSION

1. For Latvia, hydropower and bio-power constitute a particularly important source of renewable energy, which makes it possible to diminish the effect of the global warming and diminishes the country's reliance on imported energy.
2. The electricity market price is influenced by the factors related to the transmission grid as well as by environmental and legal limiting factors.
3. The technical limitations of electrical grid that are brought about by insufficient transmission capacity of power transmission lines can be diminished by building new power transmission lines or by using new transmission technologies, which will diminish the loading of the existing lines, or by building new power plants closer to the consumer load (distributed generation).
4. Strong fluctuations of energy prices on the market cause the need to change the operation and management principles of generating companies and lead to a stochastic formulation of the optimization task of power plant planning.
5. Uncertainty and random phenomena have an important role in technical and economic analysis as well as in the optimization task. Hence, the models and task-solving tools have to be stochastic. Formulation of the optimization task with an approach based on the calculation of time-average profit, simplifies the simulation of stochastic processes.
6. Optimization of power plant regime planning according to the changes in electricity prices and optimal distribution of energy resources enable the producer to gain higher profits.
7. The stochastic approach to optimal, profit-based daily and hourly energy resource planning, set out in the present Thesis alleviates the day-to-day work of the plant operator and increases the energy efficiency level of the power company.
8. Methods based on the game theory may help to make the right decision about the formation of coalition between the market players, public trader and local consumers. Fair distribution of the surplus income can be done by using the Shapley value.
9. The active power nodal prices also depend on the reactive power flows in the grid. Therefore, to maximize the welfare function, it is useful to consider the increasing of the available transmission capacity of the grid by building new lines as well as the possibilities of compensating reactive power in the grid.
10. The Thesis proposes an algorithm for solving the optimization task and calculating the nodal electricity prices, considering the inhomogeneity of the grid and reactive power flows; the approbation of the algorithm has been performed by using the example of the Baltic Power System. The results of experimental calculations prove the possibility of using the proposed algorithm.
11. In order to simplify the process of solving non-linear programming tasks, to alleviate it and speed up the computation process, the Thesis proposes to use the method of approximatory programming, which makes it possible to take into account limitations both in the form of equations and inequalities. The obtained results testify the groundedness of using the method of approximatory programming for the planning task of power system operating mode regime.

12. The results obtained in the course of writing the Thesis can be used as a basis for further development of industrially usable software and increasing the competitiveness of an industrial enterprise.
13. Summary of the results shows that, by using the proposed algorithm in optimization and modifying of the existing support scheme, biogas power plants and hydropower plants and HPPs in Latvia may receive additional income and society may receive additional benefits.

RECOMMENDATIONS FOR FUTURE WORK

The results of the present Thesis can be used as follows:

1) In developing the software complex for the regime management of Latvian power plants;
2) Regime optimization software for biogas power plants and small HPPs may become a product that is commercially widely used; to achieve this, user-friendly and convenient interfaces and user manuals are needed;
3) In harmonizing the operating regimes of Latvia's power plants with neighbouring countries;
4) In forming a coalition of small power plants and a company for its management with the goal to diminish the management costs and to more fully and efficiently use the summary power.

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