RIGA TECHNICAL UNIVERSITY
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THE ASPECTS OF THE PLANNING AND OPTIMIZATION OF ELECTRIC STATIONS OPERATIONAL REGIMES UNDER THE CONDITIONS OF MARKET ECONOMY

Summary of Doctoral Thesis

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DOCTORAL THESIS
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Doctoral thesis is proposed for achieving Dr.sc.ing. degree and will be publicly presented on the 22th of May 2014 at Faculty of Electrical Engineering of Riga Technical University, 1 Kronvalda boulevard, in room 117, at 14^{00}.

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CONFIRMATION STATEMENT

Hereby I confirm that I have worked out the present doctoral thesis, which is submitted for consideration at Riga Technical University for achieving Dr.sc.ing. degree. This doctoral thesis is not submitted to any other university for achieving scientific degree.

Renāta Varfolomejeva ....(signature)

Date ....

The Doctoral thesis is written in Latvian, it includes introduction, 5 chapters, conclusions, list of references and 1 appendix. Total number is 147 pages, which include 78 figures and 31 tables. The list of references consists of 130 items.

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TOPICALITY OF THE SUBJECT OF THE DOCTORAL WORK

The increasing of power consumption, increasing the sizes of power systems, complexity and importance of power systems, limited resources, increasing of the prices for the resources, influence of random and uncertain factors, climate change - everything brings top importance to the problems connected with power engineering, the importance of the problem became a reason of power systems restructuring at the international level, market conditions and mechanisms application in the power systems development and operation management. These tasks are very difficult for realization as power systems are one of the most complicated artificial issues existing as a result of human activities. The dimensions of the modern systems prove the necessity to change principles of the systems management. Power system is divided into many legally independent parts competing with each other. Division of the system into more parts decreases the sizes of the managed objects, provides an apparent simplification of models and algorithms of management and decision making, but at the same time gives new problems related to the influence of inter competition among the structures.

Along with legal power system division into independent elements a further integration of power systems and new linking among systems take place. From the technical point of view it could be stated that Latvian power system became a part of a large system of European and Asian continents.

Power engineering connected with restructuring and market mechanisms as well, has special swift changes in Latvia and other Baltic states. Demands of energy, prices, and standards have changed significantly. A lot of new technologies became available in the production and distribution of energy (steam-gas technologies, smart networks, smart metering and Internet technologies, dissipating generators, alternative sources, gas insulated installations, cables of new types, power electronic devices). The Baltic States are electrically connected to Scandinavians. These changes should be taken into account managing power systems.

For competitiveness stimulation international agreements, orders and regulations are accepted. Power exchange market is organized to provide a particular order under the condition of competition. Competitors on an optional basis accept coordinated regulations of the market, trying to work effectively and maximize their profit. A task of regimes optimization existed. For their solution appropriate methods, optimal control algorithms for the programs and devices should be developed. Improvement of power engineering effectiveness is for long time among the most priorities for science. World conferences are organized and thousands of papers are published in this area. New approaches, devices, models, algorithms and programs are suggested. Latvian scientists have made also a great contribution into this direction. The famous Latvian scientists in this field are: Jāņis Bubenko, Venjamins Fabrikants, Jēkabs Kuzmins, Zigurds Krišāns, Vera Bloka, Jēkabs Barkāns, Juris Ekmaņis, Leonīds Ribickis, Svetlana Guseva, Pēters Šipkovs, Viļņis Krēsliņs, Jāņis Gerhards, Kārļis Briņķis, Vladimirs Čuvičins, Viktorija Neimane and many others.

The topicality of the task of power systems regimes optimization is significantly improved under the conditions of market economy. It gives to the producers of heat and electric energy an opportunity to increase their market competitiveness, to calculate the amount of fuel and perspective structure with a high degree of accuracy, to discover the weak points of the process. Developing the tasks for optimization of the regimes of electrical stations and power systems the changing of the optimization criteria should be considered as a significant innovation. The competitive relationships in the branch of power engineering provide the improvement of the effectiveness of production, transportation and distribution technologies. The competition in the market of electric and power engineering points out the following basic areas: design and building of power objects, generation and delivery of energy, consumption of resources and obtaining of investments. To provide the competition requires large amount of private power enterprises at the market (producers and suppliers of electrical energy), free access to the electrical networks, and formation of prices stimulating the competition. The space configuration of the market is determined by the power electric system (PES) borders with specific inside connections. The effective competition requires significant reserve of the generated power and correspondent bandwidth of the electric network. Further the intensity of competition is increased with the increasing of the amount of energy producers at the particular market.

The questions mentioned above are topical in many countries, that is proved with large amount of publications devoted to the power systems management under the market economy conditions. Latvia is not an exclusion. Quite the contrary it should apply everything possible for the improvement of competitiveness taking into account small size and absence of fossil fuel. This factor determined the purpose of this paper.

AIMS AND OBJECTIVES OF THE THESIS

The aim of the promotional paper is to provide the algoritmic and informative basis of Latvian electric energy system regimes management to synthesize the software.

For the reaching the stated aim the following tasks were solved:

- modern principles of the organization of the world electric power market are overviewed, the levels of liberalization of the Baltic States electric power market and analysis of its restrictions as well as Scandinavian power market will influence the price formation in the Baltic States;
- the optimization stochastic algorithm is synthesized and proved its operation feasibility for the station regime;
- models for evaluation of Latvian power systems producers benefit for the co-generation and hydroelectric stations are synthesized; volume of the necessary information and its sources are defined; models are examined during the solving of the optimization tasks; the opportunity of the models application is proved together with the methods and algorithms of general reduced gradient and dynamic programming;
- the algorithm and software for small hydro electric stations optimization are suggested, validated and examined; the necessity to change basic scheme of small electric stations operation and possibility of its realization without violation is proved;
- the opportunity to apply Shapley distribution values realising bilateral operations at the power market is validated.

METHODS AND TOOLS OF THE RESEARCH

The following research methods and tools have been applied in the study:

- the method of generalized reduced gradient to solve the task of effective optimization of HES resources utilization;
- the method of dynamic programming for the solution of optimization tasks;
- the games theory criteria's of decision making under the conditions of uncertainty (including the coalitional games theory) and methods;
- interactive environment MatLAB, foreseen for intensive calculations, data analysis and its visual representation;

- system GAMS - high-level programming language for the realization of mathematical model and solution of the task of optimization;
- steam-gas technology's simulation „Termoflow";
- MathCAD system for the solving of engineering problems and visualization and analysis of the results;
- the program Microsoft Excel.

NOVELTY OF THE DOCTORAL THESIS AND BASIC RESULTS

The results of the general research made in this work:

- A complex model is developed for the calculation of profit of electric energy producing enterprise. For the model development the structure of producing enterprise energy sources and opportunities of electric energy import was taken into account;
- Power thermal and hydro-blocks, hydro-reservoirs are synthesized for Latvian power system, as well as models of small hydropower plant (SHPP), they are identified and the opportunity for their application for the regimes optimization is proved.
- For the first time a station regime optimization problem solution is made with the stochastic approach;
- A modified algorithm of dynamic programming (DP) method realization is suggested and proved for the achievement of maximum income of SHPP. A singularity of the algorithm is the methodology of water pressure changing determination, which determine the water consumption to particular water pressure level at each interval of the regulation cycle;
- The opportunity to apply the generalized reduced gradient method for the solution of the task of maximum income obtaining at Daugava HPP, SHPP and complex of electric stations is proved.;
- For the first time a theory of cooperative games methodology is applied in the SHPP tasks solution - Shapley value (right winning distribution among the coalition participants) On the basis of this theory the effectiveness of the SHPP support scheme overviewed and the necessity of the operational regime regulation is proved in accordance with the changes of the market prices.

PRACTICAL IMPORTANCE OF DOCTORAL THESIS

The practical importance of the algorithms and methodology suggested in the thesis:

1. The application of the developed mathematical model allows increasing of production effectiveness of active power of Baltic States in the electrical market.
2. The stated realization of electric energy producers management realization allows enterprises producing electric energy is required at the market.
3. The electric units models and regime optimization algorithms synthesized, their realization and results became a basic for the development of the task of Latvenergo electric stations regimes optimization software (agreement between RTU and JSC "Latvenergo").
4. The suggested models and algorithms allow develop special programming modules for the automatization if decision making and quality improvement with the intelligent management of regimes of small HPP, that provides maximum utilization of hydro resources of small rivers. (The latter has a great importance for the future of Latvian economy, as there are more than 200 small and middle rivers in the territory of Latvia with more than 150 places suitable for power engineering).

The results of the work are applied in the completed projects and programs and those under realization:

1. State program Power engineering (scientific advisor academician Juris Ekmanis) Project Nr.7 "**Decreasing of Climate Changing and Integration of Renewable Energy Resources Technologies into Latvian Power System**" (Scientific advisor professor Antans Sauhats);
2. Agreement (RTU with Latvenergo, signed in 2013, planned to be completed in 2015) for the investigation of AS „Latvenergo" electric stations regimes planning program development".

THE PERSONAL CONTRIBUTION OF THE AUTHOR

The working power system regime optimization task selection at free market conditions as the basic of the work was made with Professor Anatoly Mahnitko. Optimization algorithm synthesis using a stochastic approach, and cooperative game theory methodology adaptation carried out together with Professor Antans Sauhats. Electric power stations block models created by summarizing the experimental curves, which was designed together with JSC "Latvenergo" and "Siltumelektroprojekts" experts.

The results of publications, which belongs to Inga Umbrasko (see list of publications) are not included in this work.

All the calculations, the results of the analysis, optimization procedure programming and verification, presentation of results, conclusions and summarization belong personally to the author.

APPROBATION OF THE DOCTORAL THESIS

The results of the research are reported and discussed at 12 international conferences:

1. The 9th International Scientific Conference "Energy - Ecology – Economy", 18-20 May, Tatranske Matliare, Slovakia, 2010.
2. The 6th International Conference on Electrical and Control Technologies, 5-6 May, Kaunas, Lithuania, 2011.
3. International Scientific Conference „Present-day Problems of the Power Engineering", 8-10 June, Gdansk-Jurata, Poland, 2011.
4. The 6th International Scientific Symposium on Electrical Power Engineering, 21-23 September, High Tatras, Slovakia, 2011.
5. The 52nd International Scientific Conference Power and Electrical Engineering, Seminar for Doctoral Students in the section Power and Electrical Engineering, 14th of October, RTU, Riga, Latvia, 2011.
6. The 7th International Conference on Electrical and Control Technologies, 3-4 May, Kaunas, Lithuania, 2012.
7. The 13th International Scientific Conference "Electric Power Engineering 2012", 23-25 May, Brno, Czech Republic, 2012.
8. The 5th International conference on Liberalization and Modernization of Power Systems: Smart Technologies for Joint Operation of Power Grid, 6-10 August, Irkutsk, Russia, 2012.
9. III международная научно-техническая конференция: Электроэнергетика глазами молодежи, 22-26 October, Ekaterinburg, Russia, 2012.

10. The 12th International Conference on Invironment and Electrical Engineering EEEIC 2013, 5-8 May, Wroclaw, Poland, 2013.
11. The PowerTech 2013 Conference, Towards carbon free society through smarter grids, 16-20 June, Grenoble, France, 2013.
12. The 2013 International Conference on Environment, Energy, Ecosystems and Development (EUROPMENT 2013), 28-30 September, Venice, Italy, 2013.

The results of the research are reported at three seminars with the participation of Latvenergo and Siltumelektroprojekts experts.

PUBLICATIONS

The results of the work are published in 25 international editions:

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8. **R.Varfolomejeva**, I. Umbrasko, A. Mahnitko. Algorithm of spinning reserve distribution for market participants profit maximization. // Proceedings of the 6th International Conference on Electrical and Control Technologies. – Kaunas, Lithuania. May 5–6, 2011. – 145.-148. pp.
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12. **R. Varfolomejeva**, I. Umbrasko, A. Mahnitko. Algorithm of producers' profit maximization by optimal operating equipment selection, generating power and spinning reserve distribution. // Proceedings CD of the 13th International Scientific Conference Electric Power Engineering 2012. – Brno, Czech Republic. May 23-25, 2012. – 193.-196. pp.
13. I. Umbrasko, **R. Varfolomejeva**, A. Mahnitko. Modeling of the generating company behavior in energy and reserve market. // Proceedings CD of the 11th International Conference on Environment and Electrical Engineering 2012. – Venice, Italy. May 18-25, 2012. – 1070.-1074. pp.
14. **R. Varfolomejeva**, A. Mahnitko. The power distribution in the electrical power system taking into account reservation. // Proceedings of the 7th International Conference on Electrical and Control Technologies. – Kaunas, Lithuania. May, 2012. – 195.-199. pp.
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22. **R. Varfolomejeva**, I. Umbrasko, A. Mahnitko. The Small Hydropower Plant Operating Regime Optimization by the Income Maximization. // Proceedings CD of the PowerTech 2013 Conference, Towards carbon free society through smarter grids. – Grenoble, France, June 16-20, 2013. – 1.-6. pp.
23. A. Sauhats, **R. Varfolomejeva**, I. Umbrasko, H. Coban. "The Small Hydropower Plant Income Maximization Using Games Theory"// Proc. of the 2013 International Conference on Environment, Energy, Ecosystems and Development (EUROPMENT 2013). 28-30 September, 2013, Venice, Italy, 152.-157. pp.
24. A. Mahnitko, J. Gerhards, O. Linkevics, R. **Varfolomejeva**, I. Umbrasko. Small hydropower in Latvia and intellectualization of its operating regime.// Latvian Journal of Physics and Technical Sciences, 2013, Vol.50. -3.-15.pp. (Scopus, Versita, EBSCO, INSPEC)
25. A. Sauhats, **R. Varfolomejeva**, I. Umbrasko. Additional Income Distribution between Small Hydropower Plant and Public Trader Using Shapley Value.// International Conference on Renewable Energies and Power Quality (ICREPQ'14). 8-10 April, 2014, Cordoba, Spain. (pieņemts un apstiprināts)

STRUCTURE AND SIZE OF THE THESIS

The promotional thesis is written in the Latvian language. It includes introduction, 5 chapters, conclusions, 1 appendix and list of references. It contains 147 pages together including 78 figures, 31 tables. The list of references denotes 130 information sources.

The first chapter is devoted to the features of energy enterprises regimes management under the condition of electric energy market. The market organization principles are considered as well as the order-proposal optimization task under uncertainty is formulated. Different methods are described for the solution of the task of energy enterprise management. The market restriction factors typical for the Baltic States are considered.

In the second chapter the models for evaluation of co-generation and hydro electric stations benefits are developed and their identification opportunities are proved.

The prices proposals of the electric energy producers are analyzed in the third chapter. This chapter represents the obtained results of the problem solution, that define an optimal price proposals applying the criteria of the games theory for the decision making from the market participants side, taking into account the uncertainty conditions. As well as the algorithm of optimization of regime parameter is suggested.

In fourth chapter is the developed optimization algorithm for the optimal distribution of the generated power and reserve among the stations (taking into account input/output from/to electric energy market) are described. The process of station regimes optimization takes into account its technological restrictions and features. The offered the algorithm of station regime parameter optimization is approbated on the Pļaviņu HPP example.

In the fifth chapter is devoted to the problem of small HPP control regimes optimization. The task of a small HPP operation regime is solved for the maximum income within the frames of the known variation of prices at the market. A theory of cooperative games methodology of Shapley value is applied for the distribution of additional incomes among SHPP and public trader.

1. SPECIFIC FEATURES OF THE POWER ENTERPRISES REGIMES MANAGEMENT UNDER THE CONDITIONS OF ELECTRIC ENERGY MARKET

Competition improves the effectiveness of power production at the markets. The complex modern power system is divided into few independent parts competing with each other and trying to obtain as high income as it is possible. Under the conditions of competition the power enterprises should make a logical, technically and economically proved decision to survive in the market and get the benefit from the participation at the market [1]. Such decision making requires an application of correspondent mathematical methods, algorithms and tools, the analysis, proving and selection of which is considered in a separate chapter of the paper.

The planning and management of the power enterprise regimes are divided into several stages. This research (Fig.1.1) does not consider the design and building stages, assuming that the elements of a power system are assigned without taking into account very fast, controlled with relay protection and safety automatics processes.

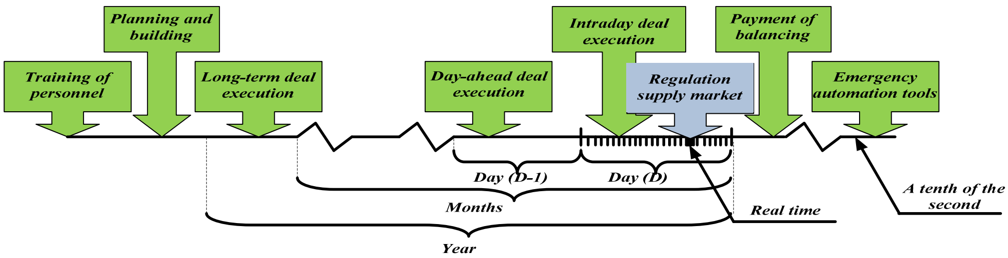

Fig.1.1 Planning and management of the power enterprises regimes

The power enterprises should consider the regime optimization task to ensure their competitiveness. This task is topical not only in Latvia, but also is important in many countries that is proved with a large amount of the scientific publication in this field. Taking into account insignificant Latvian energy systems size, fossil fuel nonbeing and it that decisions which are taken in Latvia could not cardinal change the situation at Nord Pool Spot exchange stock operation region, so it is need to use all available options to increase the effectiveness.

The task of optimization of electric station management regime can be related to multi parameter, multi dimensional, non-linear, dynamic, stochastic, discrete variables. No general assumed solution of this task exists although many simplified approaches to it are applied. The most complex task in this solution is the necessity to take into account an uncertainty in the statement of the optimization task [2, 3]. For example, calculating benefit requires the energy demands prognosis, water flow in the rivers, environment temperature, strength of the wind, etc. Decision making of the competing enterprises should be taken into account as well, that also causes the increasing of the level of uncertainty. The aim of the market participants - to obtain as high benefit as possible - can be described in the form:

$$\left. \begin{aligned} \{s_{i1}^* \ldots s_{in}^*\} &= \arg\max \sum_{j=1}^{n} E\left[R\left(s_{ij}, S_{-ij}, X\right)\right], \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \{s_{k1}^* \ldots s_{kn}^*\} &= \arg\max \sum_{j=1}^{n} E\left[R\left(s_{kj}, S_{-kj}, X\right)\right]. \end{aligned} \right\} \tag{1.1}$$

where $E(R)$ - is the average value of the benefit;

s_{ij} - the structure and parameters of the system, where the *i*-th player is chosen at the *j*-th time moment;

S_{-ij} - the selected structures and parameters of the competitors.

A typical for game theory situation is being formed as the benefit of each player depends not only on own made decision but on the other players as well. The methods of such tasks solutions are considered further. Here we will consider two specific and very important cases. The first case exists assuming a hypothesis that the market prices are not dependent on the participating player's behavior. This case meets the power market situation when a particular player is able to propose only a small amount of the energy from all the market volume. In this case task (1.1) is in the form:

$$\{s_{m1}^* \ldots s_{mn}^*\} = \arg\max \sum_{j=1}^{n} E\left[R\left(s_{mj}, X\right)\right], \tag{1.2}$$

The task of optimization is considerably simplified as it can be solved without the modeling of competitor's behavior (modeling all the behavior of competitors with the crucial prices prognosis).

The second case exists if two or more players can organize coalition to play (solve the task of optimization) together. In many situations the wishing to organize the coalition is restricted with the law (if the coalition limits competitiveness and can result in the prices increasing). But the situation changes (it is proved by the examples) if the organization of coalition reduces the prices, and therefore it is profitable for the producers as well as consumers.

The parameters of the optimal structure $\{s_{i1}^* \ldots s_{in}^*\}$ are searched for each player (at each step the conditions of the task are being changed).

1. Market "day-night ahead". Tiek meklēti $\{s_{i1}^* \ldots s_{in}^*\}$ are searched for 24 hours ahead.

The task of optimization is solved taking into account the processes at least for 24 hours. This task is divided into two parts:

- to solve the task: $\int \ldots \int R(s, X) dF(R(s, X)) = E[R(s, X)]$; and to give proposals for the market operators;
- to obtain the reply from the operator and to edit the proposal adjusting to the changes of the final information as the market prices and quantity of the energy are known.

2. Market "hour ahead". Twenty four hours form 24 steps. The day-night crucial prices and amount of the energy are known (at the first step the prognoses were known only). Solving the task at the first step the prognosis of the process ahead should be taken into account. It should be taken into consideration that if purchasing and relation to the consumer (possible through a retailer) balance is not provided, then the balancing market should be applied that is more expensive.

3. Balancing market. Unlike the previous market this is managed by the transmission system operator, the main task of whom is to provide the balance of energy.

We can prove that at all the steps the task of optimization keeps form (1.1), but the significant change of the expression should be taken into account as with additional information at each tender the applied laws of the mathematical expectation influencing parameters distribution are changed in the calculations. In addition the task solved at the first step depends on the results of the second step meaning that really the set of the tasks should be solved in a recursion form. But taking into account the three above mentioned markets are non-uniform (from Nord Pool Spot data about 95% of power is sold per day) the optimization task can be decomposed and the defined step can be considered independently (previous is independent on the further).

The solution of this task requires calculation of mathematical expectation (it is necessary to assign the probabilistic distribution function within few time periods, make correction, apply Monte-Carlo method, etc.). To avoid these difficulties the planning of regimes and management practice in many cases are transformed to the deterministic tasks statement [2, 3]. This transformation basis of comes from the equation of probabilistic theory:

$$F\ (M(x)) \approx M\ (F(x)), \tag{1.3}$$

where $F(x)$ - is a function, but x - vector of probability value. The equation is definite, if F is a linear function.

There are considerable methodological difficulties in making final decisions. There are different kinds of decision-making in the real life, depending on the scenario, but only one favourable option should be chosen.

Assume that for the uncertainty description „*n*" scenarios are selected. The optimization procedure is applied for each scenario and optimal (only for a given scenario) operating parameters and structures are found that maximize the profit R_{ij} (1.2). We will name each set of such structures and parameters as the alternative of the mode implementation (hereinafter – alternative). In result the profit matrix of the scenario-alternative can be compiled in the form of a Table 1.1. :

Table 1.1.

Game payment matrix

		The conditions of the market			
The market participant behaviour alternative		S_1	S_2	...	S_m
	A_1	R_{11}	R_{12}	...	R_{1m}
	A_2	R_{21}	R_{22}	...	R_{2m}
	...	...	...	...	...
	A_n	R_{n1}	R_{n2}	...	R_{nm}

We assume that a number of alternatives is similar to a number of scenarios, because the Table 1.1. includes only those alternatives, which at least at one scenario correspond to the maximum profit (the dominating alternatives are cast out [9]). Pareto optimality is used to select the dominating alternatives [10], which can be formulated for the task observed as follows:

The decision $s^* \in S$ may be considered (Pareto principle) as the optimal, if there is no other $s \in S$, at which $R_i(s) \geq R_i(s^*)$, at all $i = \overline{1,\ n}$ and $R_j(s) > R_j(s^*)$, at least at one $j = \overline{1,\ m}$.

A number of scenarios can be enormous. For instance, if to accept only 3 possible equilibrium prices for each hour, then the total number of scenarios will be 3^{24} per 24 hours.

The decision related to the only alternative choice should be made using a Table 1.1. The game theory criteria are used for making a final decision (see Chapter 3).

2. THE GENERATION BLOCKS EFFECTIVENESS ASSESSMENT MODELS

Features of the co-generation blocks (CHPP) modeling

Co-generation is a simultaneous production of electric and thermal energy within the same thermodynamic cycle. Often this process is called a combined production process of heat and electric energy. Basically, for co-generation process steam and gas turbines (together or separately) and internal combustion engine can be used. Both technologies are basic in Latvian power engineering (for example, combined heat power plant (CHPP-1), CHPP-2 total electric power is more than 1 GW).

This paper provides modeling of the energy production process with the aim to define benefit according to the assigned regime parameters and prices of energy. The model can be realized in two ways:

1. Applying experimentally defined characteristics [5].

Having information on the heat energy demand and environmental temperature the amount of electric energy can be calculated from the experimentally obtained characteristics and with the information of the prices for fuel and energy and exploitation expenses the benefit from it can be calculated. The experimentally defined characteristics are presented also in the table form, that gives the opportunity input it into computer and make the calculations applying one of the data interpolation types.

2. Developing a special model, which is availible to calculate the benefit in dependence from its regime and conditions (Fig. 2.1). The model's generalized flow-chart is given at Figure 2.1.

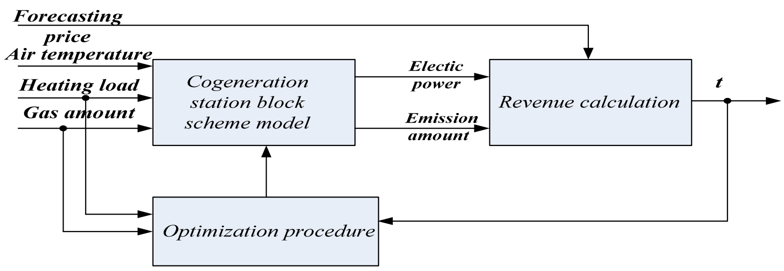

Fig.2.1 Combined heat power plant model's generalized flow-chart

Development of a special model that is able to calculate the benefit according to the regime and conditions applying existing software, e.g. internationally recognized software Thermoflow [5]. This software is aimed for the use during the designing of electric station, applying the base collecting data about steam boilers, gas and steam turbines, auxiliary equipment. The software gives an opportunity to construct own station, change turbines, boilers, other possible structures. It also gives an opportunity to determine the characteristics necessary for the benefit calculations. Using this software the structure of CHPP-2 first power block was developed (in co-operation with leading specialists of JSC "Siltumelektroprojekts" Viktor Trufanov [11]) allowing developing of the necessary characteristics with high accuracy and small sampling level. Using these data can make a data base for the implementation of the regimes optimization tasks. The model developed in Thermoflow environment gives an opportunity to calculate characteristics with different combinations of the regimes parameters with wishing detailing "*a priori*" till the optimization procedure.

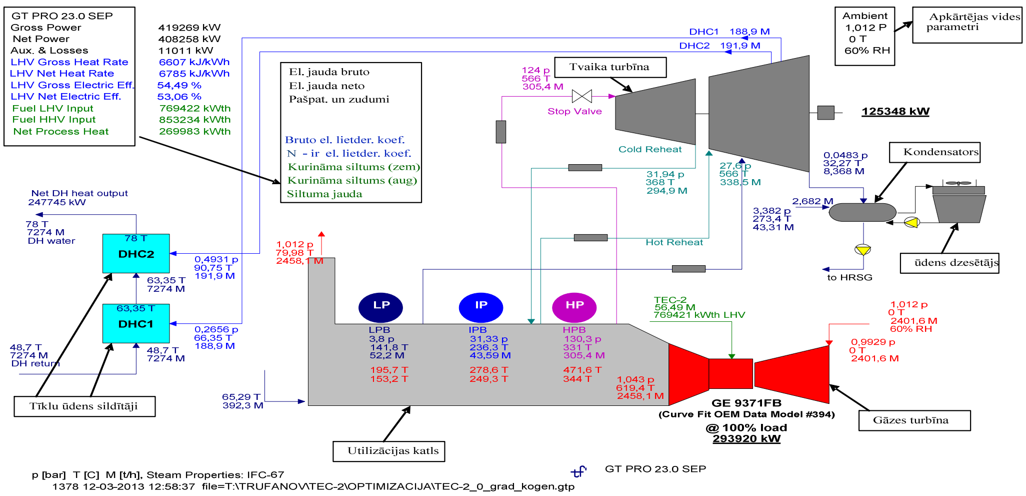

Fig.2.2. Structure of the model of CHPP-2 first power block (software Thermoflow environment)

The model is realized as an Excel table with easy access to different final data, obtained within the solving of the optimization task in programming environment.

Modeling of the thermal blocks operation should taking into account the restrictions of heating network. The results of the "*a priori*" made calculations can be used for the examination of these restrictions.

<u>Opportunities and features of hydro stations (HPP) modeling</u>

In the power systems with high specific weight of HES like that of Latvia the water storage pools can be considered as active control elements of these systems [6]. Incomplete or incorrect utilization of the hydro-resources during the day regulation period result in economic losses for the energy system. Modelling of HPP operation regime (Fig.2.3) use the characteristics describing the changes of the water level taking into account geometry of the water storage pool, water flow, power of the hydro-aggregates, their amount and parameters. These characteristics are formed in accordance with technical data of HPP hydro-aggregates and refined during the experiments. The characteristics of Daugavas HPP cascade hydro-aggregates are in the form of graphs and tables and, therefore, they can be input into computer applying some of the approximating procedures.

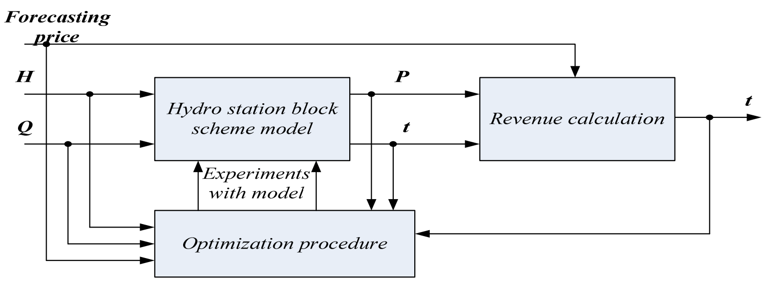

Fig. 2.3. Flow-chart of HPP managing regime benefit determination

While modeling HPP operation regimes the equations of arithmetic progressions were used:

$$H_j = H_{j-1} + \Delta t_j \cdot F\left(H_j, Q_j, \eta_j\right), \qquad (2.1)$$

where H_{j-1} - - is the water falling per hour Δt_{j-1}, m;

$\Delta t_j \cdot F(H_j, Q_j, \eta_j)$ - change of the falling depending on the amount of the reserved water or additionally reserved water amount and natural flow of water.

Managing the operation of the Daugavas HPP cascade aggregates the water flow in reservoirs should be taken into account.

Applying with this aim Gaukcler-Manning-Strockler formula [45, 46] the model of the reservoir filling (Fig.2.4) is developed (by this moment this was not taken into account managing cascade operation). For the identification of the model experiment are foreseen.

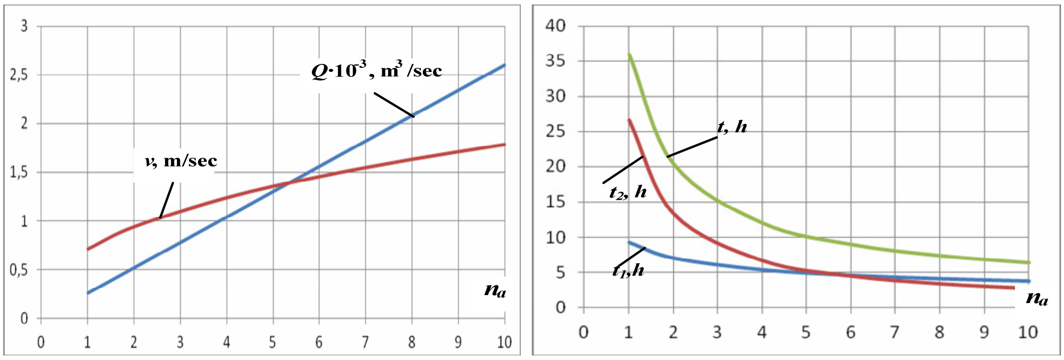

Fig.2.4. Dependence of the values on the amount of Pļaviņas HPP started up aggregates

The flow-chart of the hydro electric station operation regime optimization is in Figure2.5.

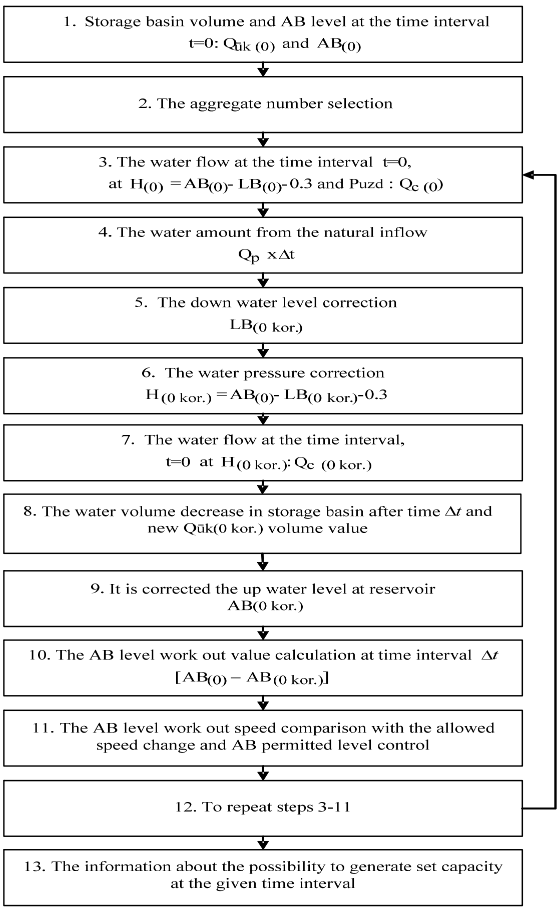

Fig. 2.5. Flow-chart of the hydro electric station model

3. TEORETICAL ASPECTS OF THE TENDER PROPOSAL OF ELECTRIC ENERGY AND REGIME MANAGEMENT OPTIMIZATION

For participation in electric energy market a producing enterprise (EPE) submits a bid price to a tender; whether the enterprise gets to the market depends on this value. Selecting a correspondent bid it is important to take into account an expected and real income risk. Further some aspects of price proposal (future - bid prices) formation for EPE are considered. As the price formation is the basic instrument of the market participation then the discussion of this problem is topical to be considered from an electric energy producer point of view. This paper is overviewing the aspect for the influence of price proposals on the changing of energy producer decision making under the market conditions.

The producer of electric energy could apply different bid price for the income maximization [8]:

1. „real price" bid that reflects an objective price of the produced electric energy and is close to the characteristics of relative expenses increase;
2. „reduced price" bid - an aggressive occupation of a part of market on condition that the prices of electric energy will decrease;
3. „increased price" bid is basically on the oligopoly markets. Because of its size or position on the market one of the enterprises is becoming a leader. This leader makes a decision on prices but the others participants accept these solutions and follow them.

We can conclude by summarizing the analysis is done, substantiated [8] by the methodology described:

Theoretically possible offers of the „reduced prices" do not occur practically within the market and competitive conditions, because the competition factor`s influence is limited as in many cases for the producers of electricity it is beneficially to reduce the production of less efficient plants and buy the power from competitors.

The impact of competitors should be taken into account while creating a tender offer and selecting the mode variables. It is gainfully to do it with the help of the equilibrium price predictions from the point of view of the simplification of the task solution optimization.

Using the optimization problem in the form of (1.2) from the first chapter, we can say that the game with a neutral opponent (nature) is carried out [2], the scenarios (prices, heat demand, the water flow in rivers) are predicted and do not depend on the chosen alternative. The task solution is made in two steps in this case:

1. The dominating alternatives are cast out using the Pareto approach. Any alternative of A_i is accepted to be the dominating one, whose elements are $R_{ij}^{*} \leq R_{ij}$ at all j.
2. A final decision is made by using one of the game theory criteria [2, 7, 12-16, 17].

We can choose one criterion out of the observed game theory criteria, in accordance with which we will evaluate one or the other decision-making to create the offer of the electricity price. We will choose the criterion of the maximum average profit value since our decision is related to profit-making within different market conditions – Bayesian-Laplace criterion.

We face large computational problems while practically applying Bayesian-Laplace criterion, because enormous number of scenarios-alternatives is possible. This problem can be solved by using the Monte Carlo method to calculate average profit [2]. Take into account that

$$M[R] = \frac{1}{N}\sum_{i=1}^{N} R_i \approx \frac{1}{m}\sum_{\gamma=1}^{m} R_\gamma \;, \qquad (3.1)$$

where γ - a random number that is equally divided ranging from 1 līdz N, but m – experiment value. Equation (3.1) accuracy depends on the value of the number m and the size of R dispersion. Accuracy increases in proportion to the value $\sqrt{m}$.

The structure of the proposed algorithm is displayed on Figure 3.1., taking into account a stochastic approach and Bayesian-Laplace criterion.

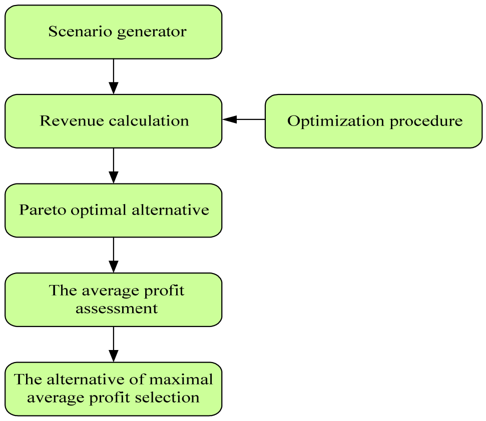

Fig. 3.1. The regime parameter optimization algorithm

The stochastic approach of the optimization task can be solved by using Bayesian-Laplace criterion and the Monte Carlo method.

4. THE PRODUCERS BEHAVIOUR OPTIMIZATION EXAMPLES

From the prices proposal (bid price) and electric energy proposal determining at the market one of the most important aspects of the energy producer behaviour is the correct selection of generating station management regime giving the maximum benefit. Nowadays in Latvia no such program support for fast and accurate optimization of a power system exists. This task is complicated and labour-intensive. In this chapter the operation of offered optimization procedure for the non-linear multi-parameter task is proved.

4.1. Algorithm of power and reserve distribution

The purpose of the electric energy producing enterprises participating in the integrated market of energy and reserve is maximizing of incomes from participating in two types of operations, taking into account the incomes additional components that can be obtained (or lost) in accordance with the correctness of competitor's actions understanding.

In order to determine the power reserve accounting benefit in the component of the producer's profit function and find the most beneficial load distribution for the system nodes the market relations among the producers are discussed taking into account the spinning reserve. The determination of the generating power and reserve distribution is made for the substitution scheme of electric power system (EPS) (in the set operation regime).

The substitution scheme (Figure 4.1.) demonstrates that EPS electric energy total consumption is $P_{\Sigma d} = \sum P_{d,i} = P_{d,2} + P_{d,3} + P_{d,4} + P_{d,5} = 560MW$. The direction of current and loop for the scheme in Figure 4.1. is assumed arbitrarily The power losses are included into the load (5% of EPS total load) [18].

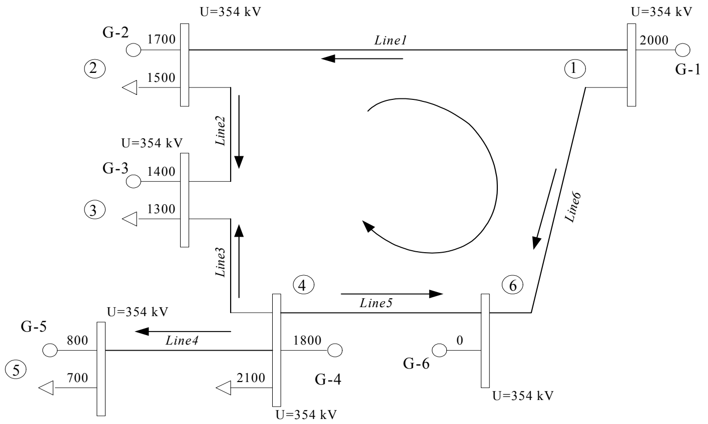

Fig.4.1. Substitution scheme of EPS optimization

The optimization of the task is made for three cases of reserve power distribution:

1. **<u>the first case</u>** considers an optimal distribution of power and reserve for all the system (taking into account an optimization criterion the most effective power distribution was selected;
2. **<u>in the second case</u>** the reserve was distributed proportionally to the generating power of the station;
3. **<u>the third case</u>** considers an even distribution of the reserve among the stations.

The characteristics of the electric station expenses are demonstrated with the parameters α_i, β_i un γ_i from Table 4.1. reflect the function of the station cost.

Table 4.1

Parameters of electric station cost function

	G-1	*G*-2	*G*-3	*G*-4	*G*-5
α_i, €	90	140	120	100	130
β_i, *€/MWh*	25	25	26	25	20
γ_i, *€/MW²h*	0,008	0,0085	0,004	0,002	0,006

Solving the task requires to take into account the technological restriction of generation (*MW*): $20 \le P_{g1} \le 200$; $10 \le P_{g2} \le 170$; $10 \le P_{g3} \le 140$; $15 \le P_{g4} \le 180$; $20 \le P_{g5} \le 80$. Generating unit *G*- is an intermediate unit and does not participate in the energy market $P_{g6} = 0$. The necessary amount of reserve power should be equaled to the highest power of the system $R_{system} = \max(P_{Gi})$ in order to provide the safety of electric supply.

We assume that the electric energy selling price in the *i*-th node taking into account the foreseen income is 30% higher than the marginal.

$$c_{G,\,i} = 1{,}3 \cdot (\beta_i + 2 \cdot \gamma_i \cdot P_{Gi})\,. \qquad (4.1)$$

The reserve price in the node can be also expressed as in [19, 20]:

$$c_{R,\,i} = 0{,}3 \cdot (\beta_i + 2 \cdot \gamma_i \cdot R_i)\,. \qquad (4.2)$$

As the task is considered for the total power system the modeling of the market requires balance prices for all the market participants taking into account maximization of the system total profit. Then the price of electric energy for the system with that proposed by producer is: $c^{P}_{market} = \max\ [c_{G,i}]$. But the price for the reserve maintenance at the market: $c^{R}_{market} = \max\ [c_{R,i}]$.

For the optimization of the task the total profit target function (Figure 4.1.) of the substitution scheme is the following:

$$B_{\Sigma} = \sum_{i=1}^{N} \left(c^{P}_{market} \cdot P_{\Sigma d} + c^{R}_{market} \cdot R_{system} - C_{G,i}(P_{G,i}) - \alpha_{R,i} \right) \rightarrow \max . \qquad (4.3)$$

where c^{P}_{market} - the price of electricity at the market, *€/MWh*;

$C_{G,i}(P_{G,i})$ - the cost characteristics of the station, *€*;

$P_{G,i}$ - the loading of the generating station during *t* hour, *MW*;

c^{R}_{market} - predicted market price for the reserve maintaining during *t* hour, *€/MW*;

α_{Ri} - the parameter of the reserve self-cost function, *€*;

R_i - the amount of reserve provided by the generating company (the enterprise maintain the generated power in the reserve), *MW*.

The proposed optimization of the model (EPS regime optimization) is made with the optimization criterion of the system total maximum profit, taking into account the expenses for the electric energy producing for each generating node. This allows define an economically profitable generation for the given loading nodes values of the scheme under consideration.

The decreasing of total income for the whole system in the second and third cases is connected with the fact that all producers (excluding the sixth as it is intermediate and does not participate in the market) were to maintain a particular amount of reserve, limiting in this way their opportunities to sell the generated power (Figure 4.2.). Therefore from the point of view of all the system total profit: first is the most effective. In this case the distribution of the reserve and generating power is realized maximizing the total system profit, for the reservation the electric energy producing equipment with the largest producing expenses is selected.

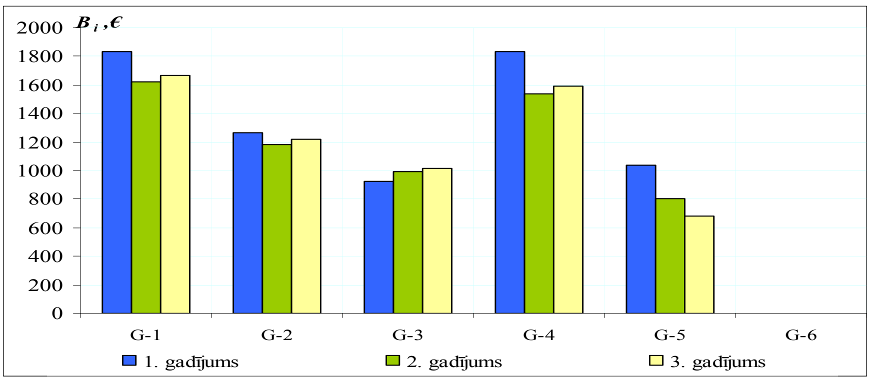

Fig.4.2. Comparison of the profit of electric energy producing enterprises in three cases

The spinning reserve is a compulsory term for safe power supply at the energy market that is why different optimization cases for total generation and reserve distribution in power system are considered. Taking into account the conditions of large amount producers at the market the power distribution needs determining of balance prices.

The obtained results of the spinning reserve allow to select an effective distribution with maximum profit for all the system [21]. As each participant of the market is concerned with the highest profit then the task when all the generated power belongs to one enterprise is becoming of top importance.

4.2. Algorithm of electric power producing enterprise profit maximization by selecting of an optimal generating stations structure

To increase the incomes of the producing enterprises at the market it is useful to calculate in complex power and reserve distribution among stations, as the separate analysis of two markets (power and reserve) can give good enough results, but not the optimal [22].

The target function of the optimization complex and optimization criterion (maximization of profit) can be expressed in the following way:

$$F = \max \sum_{t=1}^{T} \sum_{i=1}^{n} \begin{pmatrix} c_P^{market\ t} \cdot P_i^t \cdot s^t{}_{Pi} + c_R^{market\ t} \cdot R_i^t \cdot s^t{}_{Ri} - C_i^{\,t}(P_i) - C_i^{\,t}(R_i) - \\ - c_P^{market\ t} \cdot P_i^{imp\ t} \cdot s_P^{imp\ t} - c_R^{market\ t} \cdot R_i^{imp\ t} \cdot s_{Ri}^{imp\ t} \end{pmatrix} \text{ (€)} \quad (4.4)$$

where P_i^t, R_i^t - the amount of the produced or imported power/reserve of the *i*-th station during *t* hour, *MW*;

$c_P^{marke\ t}, c_R^{marke\ t}$ - predictive market price within *t* hour, *€/MWh*;

$C_i^{\,t}(P_i)$ - station cost characteristics for power production within *t* hour, *€*;

$C_i^{\,t}(R_i) = \alpha_{Ri}$ - the constant parameter of the station cost characteristics for reserve maintaining, *€*;

$P_i^{imp\ t}$, $R_i^{imp\ t}$ - amount of imported power and reserve within *t* hour, *MW*;

$s_i^{\,t}$ - Boolean variable is 1, if station participates in the market, and 0, if not [22, 23].

It is assumed that the generating stations (belonging to one electric energy generating enterprise) determine the structure of generating equipment. Everything is demonstrated on the example of substitution scheme with 3 generating stations (Figure 4.3.) and the opportunity to purchase electric energy. The changing of the total loading within a time interval is in Figure 4.4.

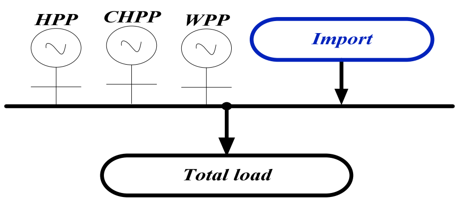

Fig. 4.3. Substitution scheme of power system

The task contains several variables and binary values. For decreasing the amount of calculations it is made each second hour within the time period from 00^{00} to 24^{00}.

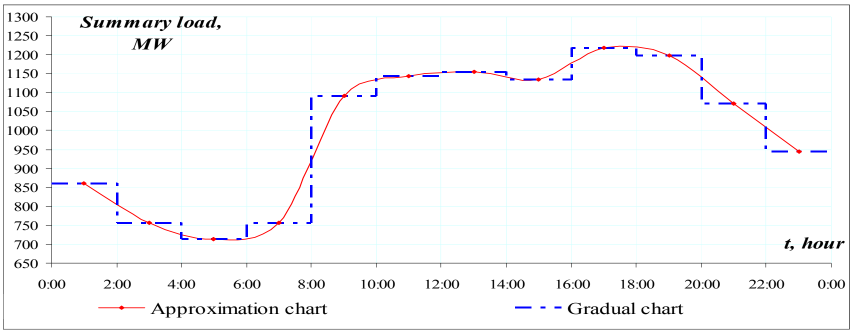

Fig. 4.4. Required amount of power at the market (changing of load)

Let us consider the selection of a generating station and the problem of electric power distribution taking into account import. The technological restrictions of the stations are given in Table 4.2, but the restrictions for import is: $P_{\max imports} = 650\ MW$. For the algorithm operability consideration it is assumed that the necessary total rotational reserve of the system active power is 5% from the load:

$$R^t_{\min i} \le R^t_i \le R^t_{\max i},$$

where $R^t_{\min i}$ - the minimum power reserve, *MW*;

$R^t_{\max i} = P_{\max i} - P^t_i \cdot s^t_{Pi}$ - the maximum power reserve provided by the station and import , *MW* [20].

Wind power stations (WPP) do not participate in reserving as they depend on the changes of the wind speed (the source of the renewable electric energy is not predicted).

Each station has restrictions for the power regulation, e.g. hydropower plant (HPP) regulation is faster (MW/sec), the combined heat and power plant (CHPP) is regulated slower (MW/min), i.e. to start slower the production of electric energy as well as slower break this production. It means that thermal electric station within the first and further hours can not produce or break the production of power more than (the task considers each second hour when the regulation power is equal to 200 MW). Therefore one more CHPP regulation restriction takes place - each second hour the changes of power and reserve can not exceed the value [22]:

$$\Delta P^t_{CHPP\,sum} = \left(\Delta P^t_{CHPP} + R^t_{CHPP} \cdot s^t_{R\ CHPP}\right) \le 200\ \text{(MW)}. \qquad (4.5)$$

It is foreseen that the present water volume can provide the operation of hydropower plant (HPP) with maximum power within all the considered time period.

Table 4.2

Technological restrictions of the power of the station

	CHPP	HPP
$P_{\min}$, *MW*	170	65
$P_{\max}$, *MW*	662	402

For the optimization of the target function the power and balance of the reserve system is taken into account:

$$P_{TES}^{t} + P_{HES}^{t} + P_{VES}^{t} + P_{b}^{t} = P_{d\,spot}^{t}, \tag{4.6}$$

$$R_{TES}^{t} + R_{HES}^{t} + R_{b}^{t} = R_{d}, \tag{4.7}$$

where P_{TES}^{t}, P_{HES}^{t}, P_{VES}^{t} - produced power of HPP, CHPP and WPP *t* per hour, *MW*;

R_{TES}^{t}, R_{HES}^{t} - HPP un CHPP reserve providing *t* per hour, *MW*;

P_{b}^{t}, R_{b}^{t} - purchasing of power and reserve *t* per hour, *MW*;

$P_{d\,spot}^{t}$ - the total load of the system *t* per hour, *MW*;

R_{d} - necessary reserve of the system *t* per hour, *MW*.

The predictive power of a wind station depending on wind is represented in Table 4.3. The table contains the data characteristics of Enercon E82 (2000 kW) generator.

Table 4.3

The total power of WPP park according to wind

Hour	Wind, *m/sec*	Power of WPP park (WPP consists of 200 generating turbines), *MW*
0:00-2:00	≈6	64
2:00-4:00	≈6	64
4:00-6:00	≈5	35
6:00-8:00	≈4	16
8:00-10:00	≈0	0
10:00-12:00	≈5	35
12:00-14:00	≈5,7	60
14:00-16-00	≈6	64
16:00-18:00	≈7	106
18:00-20:00	≈7,2	107
20:00-22:00	≈8,3	169
22:00-00:00	≈9	236

The parameters of the characteristics of the electric station expenses reflecting the expenses functions of each station are in Table 4.4.

Table 4.4

Parameters of the station cost characteristics

	CHPP	HPP	WPP
α_i, *€*	150	240	300
β_i, *€/MWh*	17	2,4	5
γ_i, *€/MW^{2}h*	0,003	-	-

In accordance with the regulations of the Cabinet of Ministers Nr.262 "Regulations of electric energy production utilizing renewable power resources, and order of price fixation", the operation price of a wind electric station during first 10 years is determined with formula:

$$C_{WPP} = 120 \cdot e \cdot k = 120 \cdot 0{,}8 = 96 \quad (€/MWh), \qquad (4.8)$$

where C_{WPP} - the price without VAT for which the public dealer purchases the electric energy (€/*MWh*) produced from the renewable resources;

e - the LVL rate defined by Latvian Bank to the European Union currency, in the considered example it is not taken into account as the calculations were made in €;

k – the differentiation price coefficient equals 0,8 if station's total set power is more than 100 *MW* [24].

The market prices for power and reserve are shown in Table 4.5. Those prices are taken from the price forecast for the next day. It is assumed, that in the predicted prices already are included HPP, CHPP and WPP output graphs, what is why prices approximately are known.

Table 4.5

Dynamics of power and reserve prices per day-night

Hours	c_P^t, €/MW	c_R^t, €/MW	Hours	c_P^t, €/MW	c_R^t, €/MW
0:00-2:00	39,9	47,88	12:00-14:00	46,9	56,28
2:00-4:00	39,3	47,16	14:00-16-00	46,6	55,92
4:00-6:00	42,7	51,24	16:00-18:00	45,9	55,08
6:00-8:00	45,3	54,36	18:00-20:00	44,7	53,64
8:00-10:00	47	56,4	20:00-22:00	42,5	51
10:00-12:00	46,6	55,92	22:00-00:00	45	54

Each value of the power system loading is defined with an optimal power and reserve distribution among the generating stations. The criterion of the optimization task is the maximization of the producer profit function (4.4).

The profit of the generating enterprise is defined in two ways:

1. **with a total optimization of the target function (profit) for the period of all 24 hours or with so called complex optimization;**
2. **with optimization for each hour separately and with further summing of the profit.**

The task of power distribution among the electric stations is considered in the work taking into account the electric energy purchasing ability of the producer (import). Two methods for the solving of this task are considered; they contain the determination of the station optimal power distribution taking into account the input/output of the station according to electric energy market component (this target function containing this component [25] is applied for the solution of the task by means of two above mentioned methods) and with this component (the solution is defined optimizing the total target function within all 24 hours period, i.e. complex optimization)..

The distribution of the power among the stations in two different cases is demonstrated in Figure.4.5 and 4.6. As it is seen from the graph the power distribution among the stations depends on the solution of the optimization task - with a summing optimization

CHPP is higher loaded than optimizing it each hour (optimizing each hour separately the power and reserve distribution depend on maximizing of these hours income only, but not on all the period).

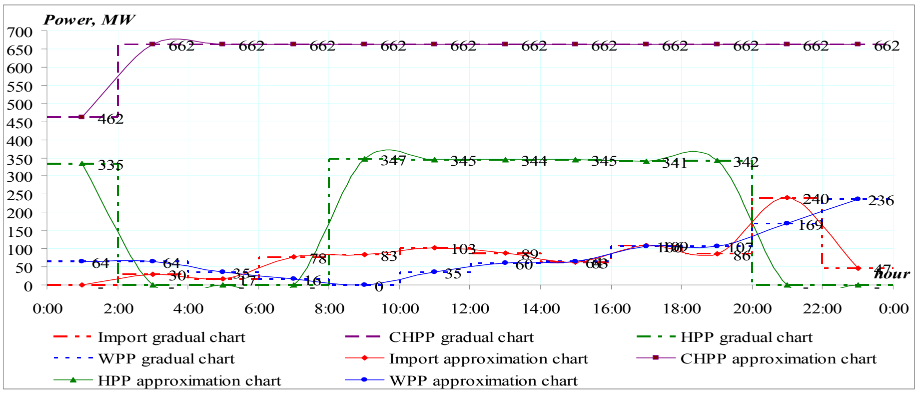

Fig.4.5. The distribution of the power among stations for the 1st case

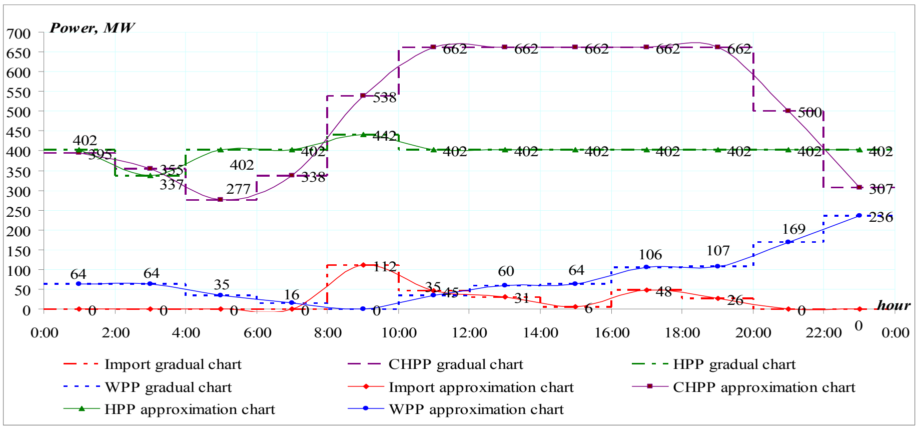

Fig.4.6. The distribution of the power among stations for the 2nd case

The distribution of the reserve in power system is shown in Figure 4.7. and Figure 4.8. Optimizing the regime for each hour separately, taking into account the station input/output electric energy market component, the reserve of the system is provided only from import, CHPP and HPP in this case does not participate in the reserve market. In the case of complex optimization (taking into account the station input/output electric energy market component) the import and HPP possible types of generation participate in the system reserve.

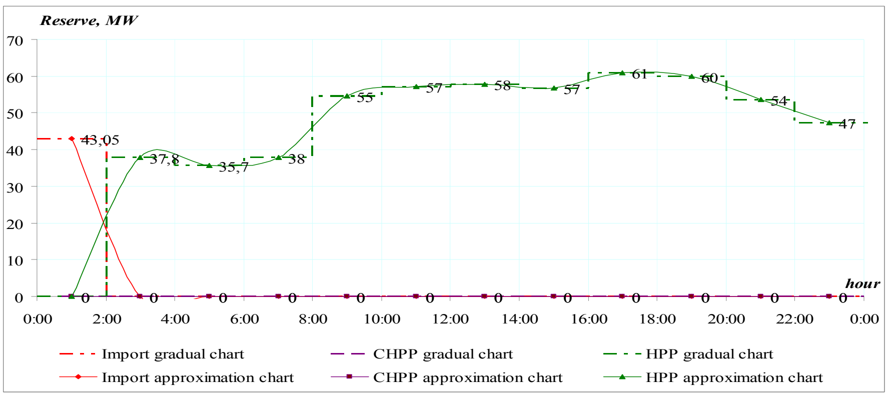

Fig. 4.7. The distribution of the reserve among stations for the 1st case

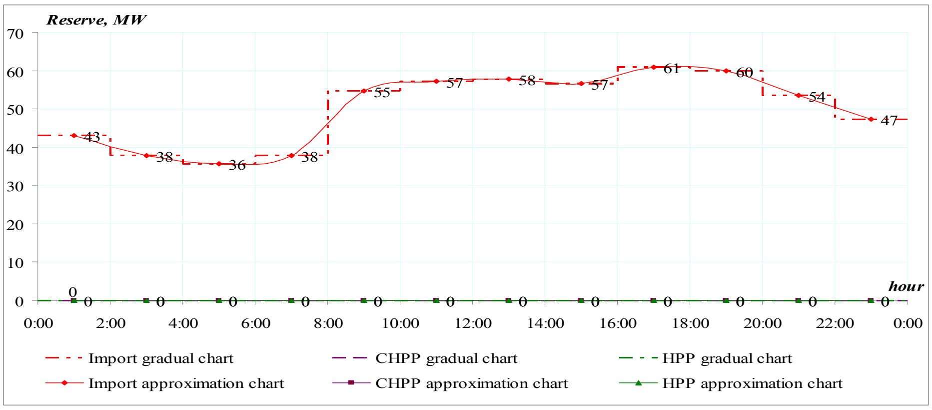

Fig. 4.8. The distribution of the reserve among stations for the 2nd case

The analysis of the optimization results states that the purchasing of electric energy is influenced not only from the market price but from the restrictions for CHPP regulation as well. Therefore the amount of the purchased electric energy (Figure 4.5. – Figure 4.10.) is not always proportional to the dynamics of prices at the market (price is in Table 4.5).

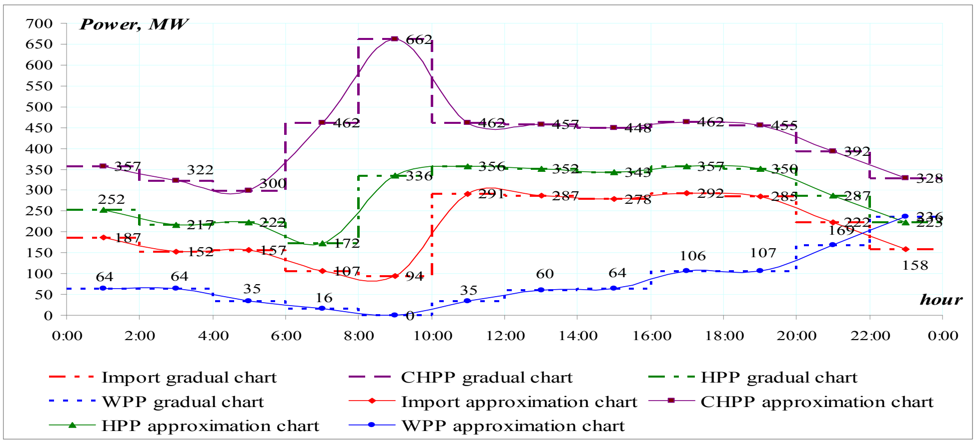

Fig.4.9. The distribution of the power among stations taking into account the station input/output electrical market component

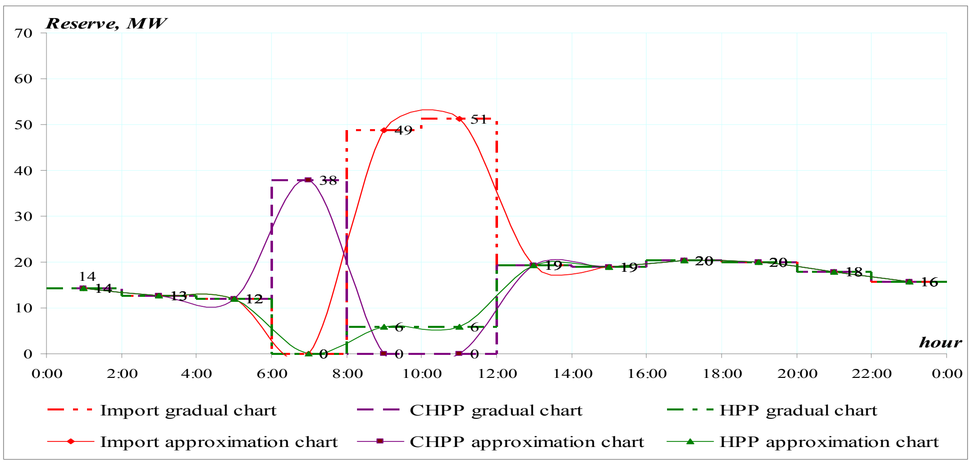

Fig.4.10. The distribution of the reserve among stations taking into account the station input/output electric energy market component

The distribution of the power and reserve with the solution without input/output component „s_i^t”,is shown in Figure 4.9 un Figure 4.10. Without this component but taking into account the power and reserve restrictions the station can not go out from the market even if at the moment the most profitable is purchasing only without production of electric energy.

The obtained results in Figure 4.11. state that the maximization of welfare function for each hour separately (the 2nd case) negatively influences the profit of the producer, as this optimization decreases the profit for 470040,15-438240,59=31799,55 €.

Relating to the influence of the station input/output market component the results state that its accounting allows to get higher total profit than without this consideration. Without the input/output component the station should produce power or maintain reserve even if this solution is not optimal.

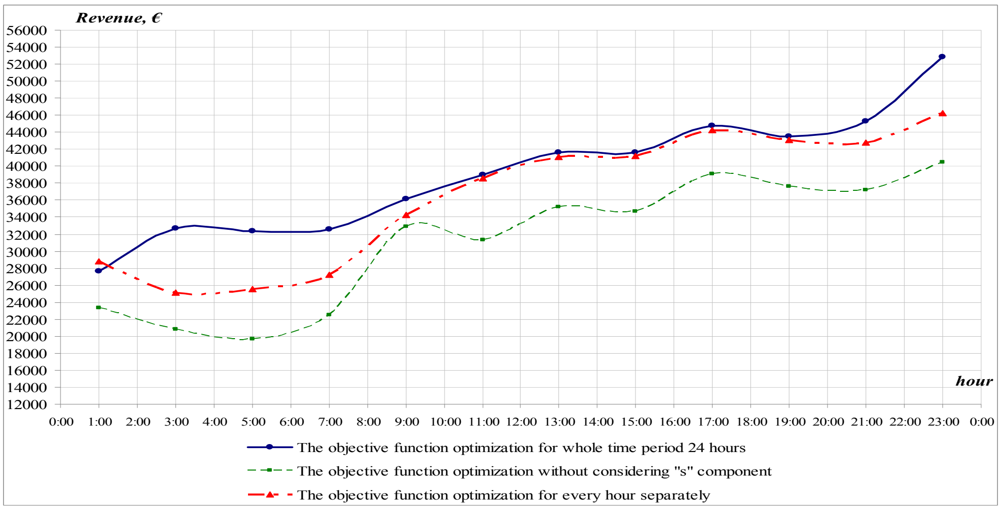

Fig.4.11. The total benefit for different types of optimization

4.3. The HPP working regime optimization example

The developed optimization algorithm for SHPP can be applied to optimize the work of HPP with a reservoir. The work optimization algorithm for SHPP is implemented on the Pļaviņas HPP. The results obtained show that adding the algorithm of the optimization mode with data on specific hydro sites between the Daugava HPP cascades; thus, it will be possible to achieve the optimization to ensure the maximum profit to Latvenergo. The calculation algorithm of HPP is summarized in the Chapter 5 (the operating mode of the Pļaviņas HPP under certain conditions of the water supply is provided in accordance with the developed algorithm).

The change restrictions of water drop in a reservoir are taken into account in the developed algorithm (possible water drop changes are accepted – 1 m per day) both after the turbine maximum water permeability and the installed maximum load on a power plant (Table 4.6.).

Check the optimization algorithm of the proposed modes offered in the previous chapter, in which stochastic approach and Bayesian-Laplace criterion were used. The optimization task of the modes is related to a huge number of the alternatives within practical environment, because it depends on the expected price scenarios (price prognostication). We offer to solve this problem with the help of the Monte Carlo method. Such power offer of choice-making methodology has not been used in the world yet.

Table 4.6

The technical data of PHPP [5]

Basic index	Pļaviņu HPP
Set power, MW	893,5
Hydroelectric set amount	10
Calculated fall, m	34-37,5
Water flow through the hydroelectric set, m^3/sek	≈ 280
Resevoir surface square at NUL, km^2	35

The calculation was made on the basis of the Pļaviņas HPP (PHPP). The process of the mode optimization is related to uncertainty, so five options of the price prognostications were selected in this example to find optimum. Five price scenarios were given for 24 hours interval, the optimum operating mode of PHPP was established depending on the price scenario; possible profit was calculated for each operating mode depending on the price change. Payment matrix was constructed after the price scenarios (Table 4.7.) for the PHPP production alternatives. The price change is shown on Figure 4.12.

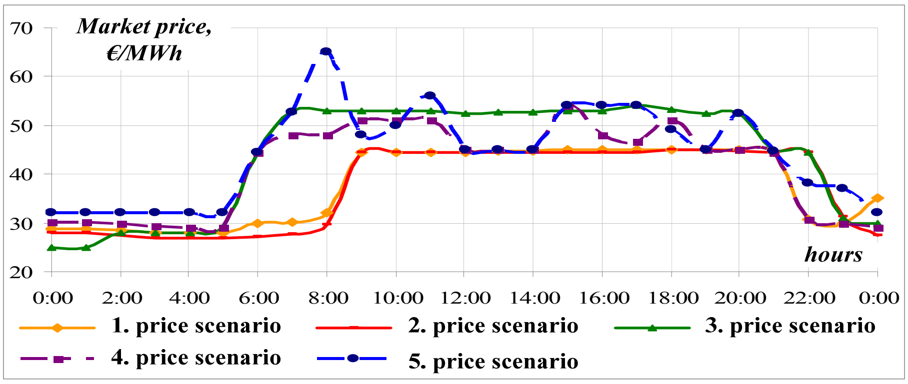

Fig.4.12. The price change chart (price scenario)

The third alternative is optimal from the Table 4.7, it means that it is required to regulate the PHPP working regime according to the third alternative.

Table 4.7

PHPP payment matrix

Alternative	S_1	S_2	S_3	S_4	S_5	Average benefit, €
A_1	203663	202870,1	238904,1	214726,1	224692,1	216971,072
A_2	197187,1	203066	233312	208119,9	215178,5	211372,712
A_3	203167,2	202089,1	241158,3	224014,5	236931,3	**221472,092**
A_4	201251,3	200718,5	239147	232266,1	231520,8	220980,74
A_5	190806	187388,5	239993,6	223313,1	254978,3	219295,907

- The power and reserve distribution is considered. Power system can not provide a safe operation without this reserving. The reserve maintaining can give additional profit. Optimizing a power system reserve should be taken into account as it can increase the incomes of the producer.
- Import supports necessary balance in the system.
- The calculations show that the solution of the optimization task is more accurate when it is calculated for all the time period like in the first case. In the second case the result is good enough but not optimal, as all the optimization period is not applied in the calculations. Some increasing in the profit during an hour results in the income decreasing during the next hour. Thus the total incomes in the 1st case with input/output component are higher than in the 2nd one.
- For the optimal reserve distribution it should be completed with the power distribution, as it provides the optimal solution of the income maximization task [22, 23].
- The price change scenarios should be taken into consideration while making the optimization of the plant`s modes to determine the most effective profit-making option

5. OPTIMIZATION OF SMALL-SCALE HYDROPOWER PLANT REGIME ACCORDING TO INCOMES FROM ELECTRIC ENERGY PRODUCTION

The problem of the hydro resources utilization will be always topical in Latvia in spite of the characteristics of the state economic system [26-29]. More than 200 small and middle size rivers are on the territory of Latvia, the potential of which can be applied in economy. Hydro-stations (5 MW or less) that use the power resources of small HPP (SHPP) relate to so called dissipated power sources. Their operation effectiveness under the conditions of market relations is defined by means of income value that is determined during the calculation period. This income can be obtained in the regime providing as large as possible SHPP electric energy production with particular water consumption within a considered period. The value of these incomes can be calculated in accordance with pre-set market prices for electric energy within the calculated period.

The essence of the SHPP regulation process is in the fact that within the separate time periods SHPP is operating with high consumption of water, decreasing the level in the river up to the acceptable limit, but during the other time periods the water consumption is lower that the water flow, therefore the water level before the dam is increasing. Usually SHPP do not have special water storage-basin in its ordinary comprehension.

During the regulation cycle independently on its duration SHPP can consume only a particular amount of water, determined by the water flow, i.e. the natural conditions. Therefore, one of the regulations of the planned SHPP regime realization is a particular amount of water consumption equal to the water regulation within the cycle period.

The changes of the water level in head water and tail-water causes the changes in water pressure at SHPP. It is connected with water consumption across the SHPP turbines. Therefore the changes of the water level should be limited $H_{\min}$ from below and $H_{\max}$ from above, i.e

$$H_{\min} \leq H \leq H_{\max} . \tag{5.1}$$

The power of SHPP can be calculated as follows:

$$P_{SHPP} = 9{,}81 \cdot \eta_{HA} \cdot Q \cdot H\ . \tag{5.2}$$

where P_{SHPP} - the power of hydro turbine, *kW*;

Q - the water consumption across the turbine, $m^3/sec.$;

H - water fall, *m*;

η_{HA} - efficiency coefficient of the hydro aggregate: $\eta_{HA} = \eta_{turb} \cdot \eta_G$, where η_{turb} - the efficiency coefficient of the turbine in relative values;

η_G - efficiency coefficient of the generator in relative values (in the calculations the efficiency coefficient is assumed constant $\eta_{HA} = const$) [27, 30-32].

Mathematically the task of SHPP maximum income achievement under the market conditions can be formulated in the following way.

It is necessary to define the SHPP operation schedule that provides its maximum income during the regulation cycle *T*

$$I(P_1, P_2, ..., P_J) = \sum_{j=1}^{J} I_j(c_j, P_j) \to \max \tag{5.3}$$

under the condition (5.1) and condition of use of the set amount of water W_J in water reservoir before dam

$$\sum_{j=1}^{J} Q_j \cdot \Delta t_j = W_J\ , \tag{5.4}$$

where $I_j(c_j, P_j)$ - ncome from sale of electricity, that is produced on SHPP during the time interval Δt_j by known market price c_j, €; *T* – the regulation cycle duration: $T = \sum_{j=1}^{J} \Delta t_j$; Q_j - the water flow through the SHPP flap during the time interval Δt_j, m^3/sec; W_J - the set amount of water m^3 that could be passed through the SHPP flap per regulation cycle *T* (day, week and etc.).

Further SHPP the SHPP operation regimes should be independent one on another during each regulation cycle *T*, because the execution of flow equality at the beginning and end of the interval is required [30, 32]

$$H_{sak.,J} = H_{beig.,J}\ , \tag{5.5}$$

If the day-night cycle of SHPP regulation is $\Delta t_j = 1$ per hour the production of electric energy at SHPP in the *j*-th time interval Δt_j is defined as: $P_j \cdot \Delta t_j$. With a particular natural water flow Q_{flow} causing the increasing of the water level in the river, the water consumption during each regulation cycle is determined by the value Q_j - operation water volume m^3 in accordance with fall changes.

Taking into account (5.2) and taking into account the water pressure before dam at SHPP within the *j*-th time interval Δt_j is changed according to the amount of operating water through the turbine [33, 34], the SHPP power can be expressed as

$$P_{SHPP\,j} = 9{,}81 \cdot \eta_{HA} \cdot Q_j \cdot (H_{j-1} \pm \Delta H_j), \tag{5.6}$$

where H_{j-1} - the water fall per hour Δt_{j-1}, m;

ΔH_j - the fall changes according to the amount of used or additonal collected water (or $\Delta h_j = \mathrm{var}$, m) and from the natural water flow in the river $Q_{piepl.} = const$, m^3/sec (it is defined with the water level increasing on the surface of the dam $\Delta h_{piepl} = const$, m), m.

5.1. Task statement

The correctness of the developed algorithm is demonstrated on the example of the Bērzes river HPP regime optimization. Basic data of SHPP: maximum water level before the dam - 8.2 *m*; SHPP power - 300 *kW*; efficiency factor of the hydro aggregate - 85%; average water flow per year - 2,4 m^3/sec and amount of water in reservoir - 274000 m^2. In accordance with the requirements of Latvian nature protection regulation the admissible minimum water level of Annenieku SHPP before the dam is 7.9 *m* [26, 36- 38].

In the additional calculations of the basic data of SHPP the graphs of the prices changes within the correspondent time period are applied. The operation variants of SHPP operations are compared with different hydro resources conditions. The obtained results prove that for the optimization of SHPP operation regimes in accordance with the profit value and operation graph the application of intelligent control system is purposeful.

5.2. Task solution with the dynamic programming method

The SHPP income increase task with considering water inflow and water storage before the dam (at the given water level restrictions) is calculated with dynamic programming method.

As dynamic programming method (DP) optimization is made with some step value, the result depends from that chosen value [35]. The decrease of the water level step value of the dynamic programming method gives more accurate result (Figure 5.1. - Figure 5.3.), but the labour-intensity and the time required for the calculations are increased [33, 34].

Making an optimization with the method of dynamic programming and step 0,025m the income of SHPP is 192,23 €.; selecting the step 0,0125m the income is increased to 196,26 €. The calculation of SHPP regime is more accurate with the step 0,01m and the income is 196,86 €.

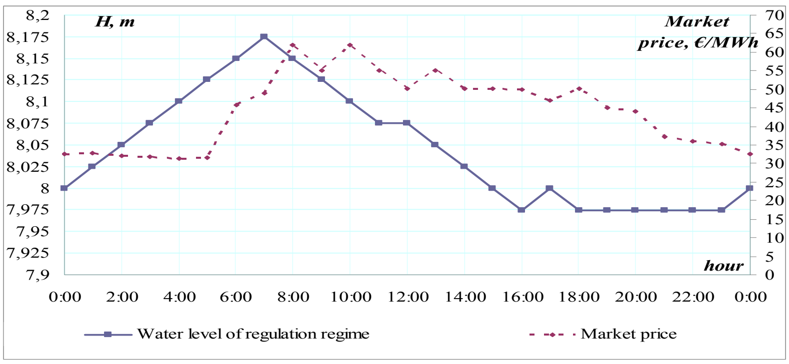

Fig.5.1. The level of water realizing optimization by means of DP method and step 0,025m

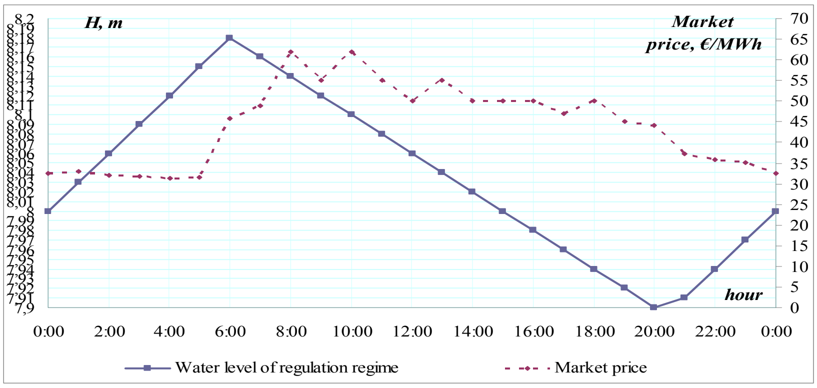

Fig. 5.2. The level of water realizing optimization by means of DPmethod and step 0,01m

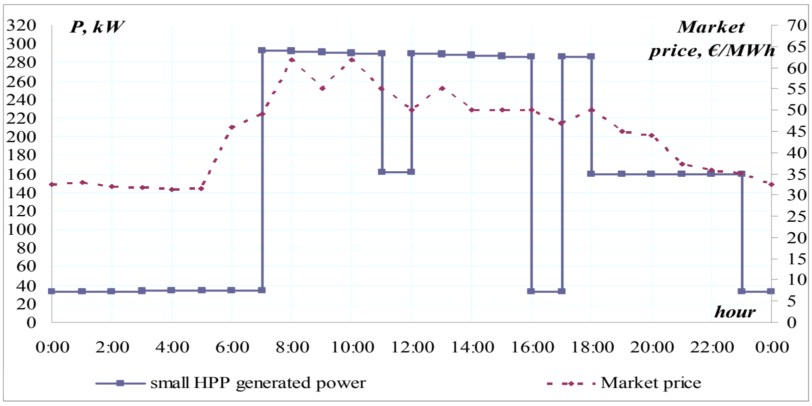

Fig.5.3. The generating power realizing optimization by means of DP method and step 0,025m

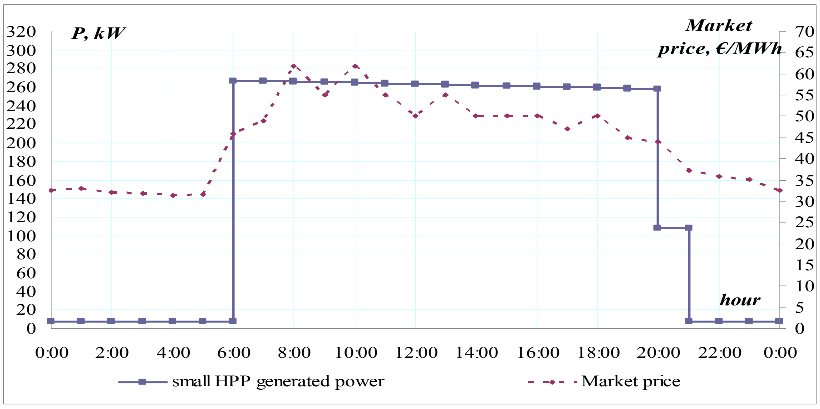

Fig. 5.4. The generating power realizing optimization by means of DP method and step 0,01m

Realizing the calculations in this optimization task by means of dynamic programming method the initial parameters can not contain the off condition of the SHPP present opportunities, the water level is increasing each hour for 3,15 cm but the selected value of the step does not allow taking into account these changes. Selecting the step 2,5 cm the possible water level increasing is only 2,5 cm, but the rest of the water amount the station utilizes producing 33 kW power, but being not fully in off condition collecting the water.

The value of step of the water consumption changing should be coordinated with the raising of water level as a result of each hour natural flow as well as the limitation of level before the dam. All these data allow select the step value and obtain more accurate results [33, 34].

5.3. Task solution with the generalized reduced gradient method

Optimizing SHPP operation regime with the generalized reduced gradient method (GRG), in the case of market price registering also two possible methods for the income obtaining are considered: taking into account only the natural water inflow the SHPP work is made without its regime optimization with using water of inflow each hour; and taking into account the natural inflow and the water collecting opportunity before the dam at the water level restrictions term – is made SHPP working regime optimizations. Realizing the optimization taking into account the water collecting before the dam and natural flow, the incomes are increased for: 200,18-171,42=28,76 €. It is very important for SHPP (additional incomes) - 14%, thus while optimizing it is topical to take into account not only the natural flow in the river, but the opportunity to collect the water before the dam.

The obtained results (Figure 5.5. - 5.6.) provide a conclusion that SHPP collect the water before dam in the case when the prices at the market are not high and utilize the water when they are, taking into account the restriction (5.1), as well as limitations for the maximum power.

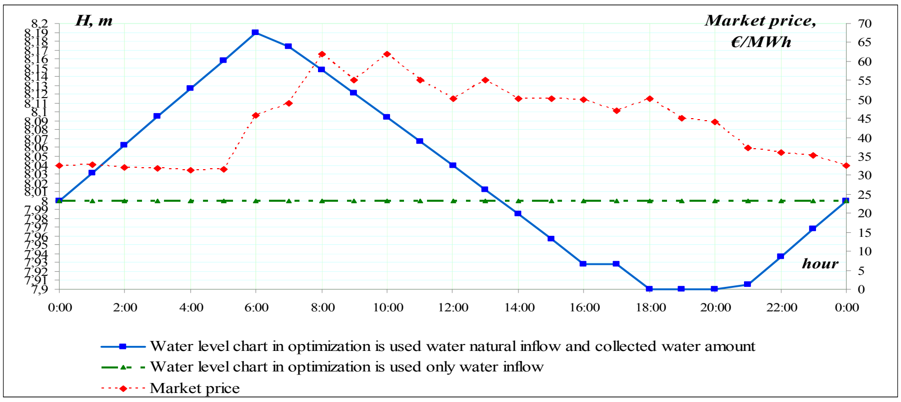

Fig.5.5. The changes in the water level realizing the optimization by means of the GRG method taking into account the market prices calculation

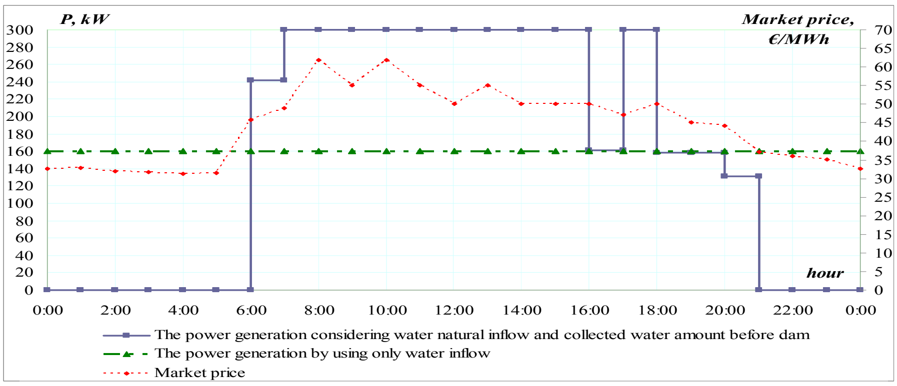

Fig.5.6. The generated power realizing the optimization by means of the GRG method taking into account the market prices calculation

- The maximum income of SHPP can be achieved realizing the operating regime in accordance with the changes of the prices for the electric energy.
- From the exploitation point of view during the period of low prices SHPP is off and collects the water in head water. At the same time the restrictions for the natural water

flow in small rivers as well as possible amount of water that can be consumed during day-night should be taken into account.

- The method of the generalized reduced gradient integrated into the non-linear programming solver does not depend on discretization, i.e. on the value of step of the water level [33, 34].
- Optimizing the operating mode of SHPP with the generalized reduced gradient, income is 200,18 €, which is higher for 3,32 € than implementing the control algorithm of the SHPS with dynamic programming method.

5.4. The distribution of additional income by shaping a coalition between the public trader and the electricity producing company of SHPP

Within the present circumstances, when all Latvian SHPP sell the produced electricity within the framework of compulsory purchase at fixed price, its operation mode is not dependent electricity price in the market. It is the largest lack of this support scheme. The experiment of the coalition establishment was carried out in order to point out the need to review the support principles of SHPP. The experimental results show that the coalition creates opportunities for the public trader and SHPP earns additional income from the adaption of operating schedule of SHPP to the electricity market price schedule [1].

An coalition creation between SHPPs and public trader give the opportunity to them to get the additional income and at the same time set up the task of this income distribution among coalition members [40-42].

It is necessary to determine its potentially earned additional income in order to motivate SHPP for participation in the coalition. The paper provides solution of this problem by using cooperative game theory (Shapley value). The use of Shapley value to share additional income between SHPP and the public trader has not been previously observed in Latvia or elsewhere in the world.

The optimization algorithm of SHPP operation is provided in this chapter. In this case, the optimization mode of SHPP should be both performed at fixed price of compulsory purchase (accordingly to the maximum power generation) and at market price (accordingly to maximum income)

A coalition does not require the repeal of the existing legislation on support of renewable energy sources. At the same time the results of this work can be considered as an argument for amendments of legislation in the future.

A coalition of players cooperates, and obtains a certain overall gain from that cooperation (an additional income from collaboration in the coalition). The Shapley value provides one possible answer to this question. To formalize this situation, we use the notion of a coalitional game: we start out with a set N kopu (S coalitions) (of n players) and a function $v: 2^N \rightarrow \mathrm{R}_{with}$ pie $v(\emptyset) = 0$, where $\emptyset$ denotes the empty set (without coalition). The function v that maps subsets of players to reals is called a characteristic function.

The Shapley value is one way to distribute the total gains to the players, assuming that they all collaborate. According to the Shapley value, the amount that player i gets given a coalitional game (v, N) is

$$\phi_i(v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!\,(n - |S| - 1)!}{n!} \left(v(S \cup \{i\}) - v(S) \right) \qquad (5.8)$$

where S - the coalition of players;

$v(S)$ - the worth of coalition S, describes the total expected sum of payoffs the members of S can obtain by cooperation;

n - is the total number of players and the sum extends over all subsets S of N not containing player i. In case if coalition is formed by all participants and coalition is known, it is not necessary to determine mathematical expectation of different coalition's variants [3, 43].

Two SHPPs and a public trader were used to establish the coalition, solve the given task and for the visuality of Shapley distribution application.

The operability of developed algorithm is illustrated on the example of two SHPP regime optimizations.

1. The first SHPP main data which allows its regulation is given: the maximal level before the dam – 8,2 m; nominal capacity – 300 kW; the year average inflow into the water reservoir – 2,4 m3/sec; the minimal level of the water before the dam 7,9 m [26, 36- 38].

2. The second SHPP main data which allows its regulation is given: the maximal level before the dam – 8,3 m; nominal capacity – 500 kW; the year average inflow into the water reservoir – 3,0 m3/sec; the minimal level of the water before the dam 8,0 m.

The SHPP income is found for regime regulation considering water inflow and water level restrictions – SHPP optimizes its working regime. Because generalized reduced gradient method (GRG) method usage can provide more accurate result than DP , the results have been found by using GRG and does not depend from the discretization, i.e. water level step value [34].

In respect that first 20 years from the date of taking of the decision to grant the SHPP the right to sell the produced electricity within the scope of mandatory procurement, SHPP sells electricity at feed-in tariff, so it is actual to optimize the power station operation regime at a constant price value (0,18 €/kWh) [39]. In this case, SHPP increases its income by maximizing power production.

The income at feed in tariff (from optimization considering the natural inflow and the ability to store up water) for the first SHPP is about 703,24 €, but for the second SHPP is 891,415 €.

The public trader (AS "Latvenergo") buys and sells electricity in the Nord Pool Spot exchange stock and should buy all electricity produced under mandatory procurement. As previously mentioned, SHPPs are not interested in harmonizing of their power generation schedule to the market price schedule, as produced energy has the same price at all time. They produce electricity at their own discretion and can work at full capacity in the hours with minimal load that adversely affect public trader. That is why it is important to optimize regime of SHPP considering price changes in the market (for example Nord Pool Spot) [1].

The additional income from the participation at different types of coalitions is got from the difference of produced electric energy in two optimization cases (at first case of feed-n tariff the SHPP increases their income by producing the maximal electric energy at all 24 hour optimization period, but in second case of market condition the SHPP produce power only in hours of maximal market price). To motivate SHPPs to work according to the market price schedule public trader share this additional income with SHPPs. Surely, SHPPs sell produced electricity to system operator at the feed-in tariff.

The income at market price (from optimization considering that the SHPP produces power in dependence of the market price, but sell produced electricity at fixed tariff) for the first SHPP is about 692,94 €, but for the second SHPP is 875,757 €.

The public trader (player 3) buys electricity from SHPPs, and if it is not in coalition with them, this player gets nothing $v(3) = 0$ €. If SHPPs are not in coalition with public trader, they get the income from selling electricity by feed in tariff: the first SHPP (player 1) – $v(1) = 703{,}24$ €, and the second SHPP (player 2) – $v(2) = 891{,}42$ €. If there is the coalition of two SHPPs, the summary income is $v(1,\ 2) = 1594{,}65$ €. The coalition of the first SHPP with the public trader brings an income $v(1,\ 3) = 713{,}43$ €, accordingly, the coalition of the second SHPP with the public trader brings an income $v(2,\ 3) = 910{,}51$ €. The coalition of all three companies would provide the income $v(1,\ 2,\ 3) = 1623{,}936$ €. In that way the gain of all coalitions can be determined as: [1]:

$$v(S) = \begin{cases} 703{,}24, & S = \{1\} \\ 891{,}42, & S = \{2\} \\ 0, & S = \{3\} \\ 1594{,}65 & S = \{1,\ 2\} \\ 713{,}43 & S = \{1,\ 3\} \\ 910{,}51 & S = \{2,\ 3\} \\ 1623{,}936 & S = \{1,\ 2,\ 3\} \end{cases}.$$

Co-operative game (v, N) is called relevant if [97-100]

$$\sum_{i \in N} v(i) < v(N). \qquad (5.9)$$

For the insignificant value of n the calculation process of the Shapley value is easy to describe in table form (Table 5.1) [1].

Table 5.1

Participant income determination

Variations	The participants income, €		
	1	2	3
1, 2, 3	703,237	891,415	29,283
1, 3, 2	703,237	910,509	10,189
2, 1,3	703,237	891,415	29,283
2, 3, 1	713,427	891,415	19,094
3, 1, 2	713,427	910,509	0
3, 2, 1	713,427	910,509	0
Average income	708,332	900,962	14,642

The result (Shapley vector) is given in the last row of the Table 5.1:

$$x = (x_1\ ,\ x_2, x_3)^T = (708.33,\ 900.96, 14.64)^T.$$

The example with Shapley values application demonstrates that the participants (SHPP) can additionally get income from the cooperation with a public merchant. In the case when SHPP manages its regime in accordance with the market prices, then, firstly, it positively influences the public merchant (who buys and sells electric energy at the market) and, secondly, the managing of the correspondent regime gives an opportunity of additional benefit. Then the maximum incomes of SHPP can be obtained from the regime managing according to the dependence of electric energy prices changing [1, 4].

With the method of reduced gradient the results calculated according to the SHPP generated power are more accurate, therefore the conditions of the usage of the hydro resources meet the technological process of SHPP operation better. From the analysis of the results we can conclude that taking into account the limitations of the consumed water the station can be short-time disabled. This time can be used for maintenance operations at the station [44].

CONLUSIONS AND RECOMENDATIONS FOR THE FUTHER WORK

1. The application of the model of economic competition relations of the electric energy entities and the restructuring requires the necessity to change the evaluation criteria of optimal regime. The target function of the regime optimality determines the condition of the welfare for all participants of the market. The maximum of this function defines the total income (profit) of the market participants.
2. The basic approaches to the formation of prices proposals of the electric energy producing enterprises are investigated. An approach to the selection of an optimal strategy of the generating enterprise is developed applying the theory of decision making.
3. The tasks of bilateral deals cause the situations profitable for partners coalition organization, in these cases the approaches of co-operative game theory should be applied (Shepply value).
4. The selection of the optimization procedure is a complicated task. These are selected for further examining from hundreds of existing algorithms: the algorithms of reduced gradient and dynamic programming.
5. The stochastic optimization task under consideration can be solved applying an approximate transformation leading to deterministic positions. In this case a scenery approach should be used. In this case a scenery approach should be applied. The opportunity to apply such transformation should be examined solving particular tasks.
6. The tasks of regimes optimization impact the loads changes and stochastic processes of the renewable power resources energy generation.
7. The algorithm for the selection of a generating station at the market is developed, taking into account the technical restrictions for the generating power and reserve. The algorithm is examined by means of a substitution scheme optimizing two cases of the profit calculation (with a complex optimization for all the periods and with optimization for each hour separately). The solution of the optimization task is more accurate when it is calculated for all the time periods (as it takes into account the total distribution of power and reserve per period). Optimizing the generated power and reserve distribution among the stations the general algorithm should take into account the market component of the station input/output at the market. Off course, this kind of algorithm can be conformed in particular market needs.

8. The optimization of Riga TES is widely influenced by the regimes and restrictions of Riga thermal system. The simplification of the task is possible taking into account the results of preliminary realised hydraulic -regimes.
9. The changing of the Daugavas cascade HES reservoir level depends on the number of the operating aggregates, the proposed model of the processes requires measurements and experiments for the evaluation of accuracy.
10. The number of the Daugavas HES cascade generators results in high difficulties in the realization of the optimization procedures. It requires a searching for simplifications for the ranking of generators combinations in accordance with effectiveness.
11. For the optimization of Daugavas HES cascade generators regimes the prognosis for time considerably exceeding 24 hours should be taken into account.
12. The input of the power blocks characteristics into computer can be realised applying the polynomial of the second range or the linear approximation and least-squares method. The specification of the algorithms requires numerical experiments.
13. The made numerical experiments demonstrate ability of the reduced gradient methods to solve the tasks of optimization for a particular station and a small stations with restrictions in the cases of optimization. For such statement the optimization of Latvenergo stations complex requires additional experiments.
14. Comparison of the results of optimization and applying two significantly different methods (reduced gradient method and dynamic programming) proves the convergence of these methods, for reaching maximum SHPP incomes while participating in the market. The adequacy of generalized gradient method application if observed for the SHPP operation (control) regime

Future work

1. Using the results of the thesis, models and algorithms to create a workable software (safe, user-friendly, with comfortable interfaces, efficient) of Latvian power electric station short-term regime planning and optimization, to perform the necessary experiments with the model for further its examination and identification, to prepare the training courses for users and students.
2. Using the Latvian electrical power station regime planning and optimization software synthesis experience and results, to carry out its improvement and to develop an exportable software package, which can be adapted to the other energy system needs.

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