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METHOD FOR DETERMINATION OF DAUGAVA HPP CASCADE HYDRO UNITS' CONTROL OPTIMIZATION

Summary of Doctoral Thesis

Riga 2006

USED TEXT ABBREVIATIONS:

- HPP - hydro power plant
- HU - hydro unit
- SG - synchronous generator
- SK - synchronous compensator
- LE - Joint Stock Company "Latvenergo"
- LE CDD - "Latvenergo" Central Dispatcher Department
- DC Baltija - Dispatcher Center "Baltija"
- GRA - generator operational mode automation

GENERAL DESCRIPTION OF THE WORK

Actuality of the work

Power industry is the leading branch in Latvia's national economy. Latvia's power system is operating in joint Baltic state's association and in joint system with Russia and Belarus power systems.

Consumption of energy resources in Latvia is greater than produced amount. The import value of Latvian primary energy resources balance in last years is 65-70% from total energy consumption. The balances of electric energy components are Joint Stock Company "Latvenergo" generated electric energy and imported electric energy. Electric energy is generated in two steam power plants: reconstructed SPP1 and SPP2, and in three Daugava river cascade hydro power plants. The largest amount of electric energy is produced by Daugava **HPP** cascade (see Fig. 1).

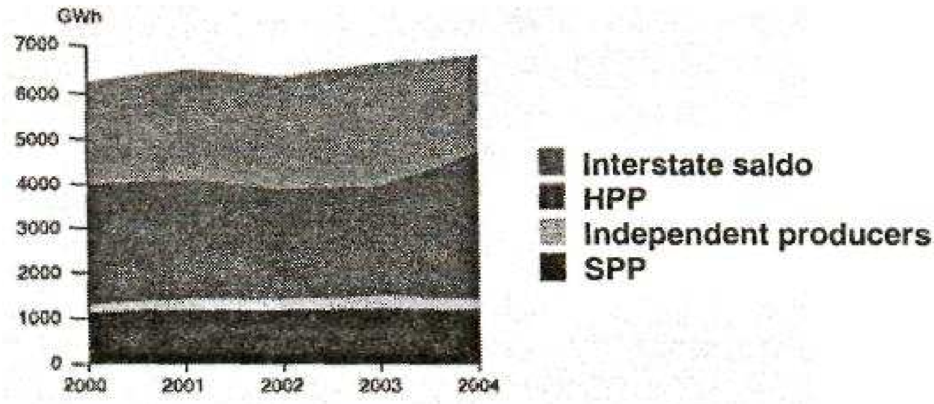

Fig. 1. Electric energy sources in Latvian power system.

Depending on water inflow in the Daugava annual production of electric energy by hydro power plants vary from 1 800 GWh to 4 500 GWh.

Electric energy generation by Latvian hydro power plants is notable resource for all Baltic States, but **its generation forecast from the supply reliability point of view is complicated.** Daugava river basin feature is sudden inflow changes not only during the years and season's but also in shorter time periods.

Modern tendencies in electric power market and power system development leads to rise in energy resources price that respectively increase the price of electric energy. Planned

Ignalina nuclear power plant shutdown also will cause problems of electric energy use and planning.

The economical usage of the Daugava river hydro power plant cascade resources in such circumstances will give notable economic effect. Although there is no possibility to forecast amount of water in the river, then on existent Daugava HPP generated electric energy amount, by managing hydro power plant unit control optimization it can be achieved notable economic effect.

*At the present moment Daugava **HPP** units are operating only keeping nominal output power values despite of optimal operational condition possibility.* Hydro units generate electric energy according to nominal generator output power. Such operational condition is not optimal because hydro unit operating parameters (water flow, water head, efficiency coefficient etc.) varies during the unit operation. That is why optimization of hydro unit operation condition is actual problem.

Besides solution of economical problems, the Daugava river HPP optimization also solves technical problems: operation in optimal mode will minimize mechanical vibrations which decreases hydro unit depreciation period, accordingly improving energy supply reliability; minimizes power oscillations, wherewith provides better power quality. Important technical problem is to determine real water head value that is also solved during the investigation.

Understanding actuality of power resources effective use problem as well as power system operation control optimization problem solving, JSC "Latvenergo" approve "Basic Business development program until year 2012", which chapter No.3 "Latvenergo basic business technical development" prescribes "Hydro power plant generating process **automactical control system modernization",** "Equipment structure and **power optimization accordingly to the expected load."**

JSC "Latvenergo" generation direction technical policy **main aim** is to achieve larger hydro power plant competitiveness in the free power market. Generation technical policy basic tasks are to **optimize plant's economical operation,** and also purposed increasing generation amount, at the same time providing all quality requirements and keeping environmentally friendly generation policy.

Objectives and goals

The objective is to increase the Daugava HPP hydro units' efficiency of operation condition control, by economical and technical parameter optimization. To reach the objective, there were solved main tasks as follows:

- Investigation and analyses of basic requirements for Daugava HPP cascade hydro power plant function, operational condition and control.
- Analyses of Plavinas HPP hydro unit parameter investigation and governor structural schemes.
- Survey of existing methods for power system control optimization with objective to clarify existing power system control optimization method point and application sphere.
- Riga HPP and Plavinas HPP hydro unit operational condition optimization possibility's analyses and development of hydro unit optimal control algorithm. Plavinas HPP hydro unit optimal operational power determination according to the corresponding water head value.
- Analyses of possibility for Plavinas hydro power plant unit participation in frequency control (power system operative instantaneous reserve), considering optimization conditions.
- Daugava HPP cascade hydro power plant automatic optimal control system scheme development. Daugava HPP cascade single hydro power plant operation condition optimization influence on the rest of the two plants operation conditions investigation.
- Optimization controller operation algorithm, which realize optimal power distribution between plants, development considering defined for cascade constraints at that power distribution. Optimal power distribution between cascade plants algorithm logical scheme development.

Methods of the research

- Basic approaches of power system hydro unit control theory.
- Investigation of hydro unit model and generation operation curves using semi-graphical method, analyses and investigation of further processing possibility.
- Mathematical simulation using Microsoft Excel software. Matlab software.

- Statistic analyses of hydro unit real operation parameters.
- Practical tests of hydro unit's operation conditions and measurements on site.
- Synthesis of the Daugava HPP hydro unit's control methods optimization methodology and development of optimal operational algorithm.

Scientific novelty

- Developed and proposed semi-graphical method to estimate hydro unit operation efficiency evaluation.
- As a result of analyses and simulations, hydro power plant unit's optimization method is obtained.
- Developed and proposed hydro unit's real water head determination method, which can be used for optimization of Plavinas HPP hydro unit's operation. Method is acknowledged as Latvia's Republic patent.
- Methodology is developed for the Daugava HPP cascade hydro power plant operational condition optimization.

Practical importance of research

As a result of analyses and modeling, developed method for Plavinas hydro power plant unit's operational optimization and developed methodology for the Daugava HPP cascade hydro power plants' operational condition optimization, can practically be implemented in JSC "Latvenergo" "Generation", accordingly with the "Basic Business development program until 2012", which is approved by JSC "Latvenergo".

Approbation

The main results of research are presented at the following international conferences:

- *"Feasibility of the Daugava Hydro Power Plant's Participation in Frequency Control",* 11th International Power Electronics and Motion Control Conference EPE-PEMC 2004, Riga, Latvia, September 2-4, 2004;

- *"Electric power system frequency and active power control dynamic problems"*, 6th International Conference CONTROL OF POWER SYSTEMS '04, Strebske Pleso High Tatras, Slovak Republic, June 16-18, 2004;
- *"Optimization of the Daugava hydro power plants' control methods",* International Scientific Conference, Riga Technical University, Riga, Latvia, from the 9th to the 11th of October 2003;
- *"Dynamic's Problems of Frequency and Active Power Control in Electric Power System",* IEEE Bologna Power Tech 2003 Conference, University of Bologna, Bologna, Italy, June 2003;
- *"Optimization Method for Control of Hydrogenerators",* International Symposium MEPS 02, Wroclaw University of Technology, Wroclaw, Poland, September 2002.

Research work content was reflected in 11 author publications:

Referred publications:

1. V. Chuvychin, N. Gurov, A. Skutelis *"Feasibilty of the Daugava Hydro Power Plant's Participation in Frequency Control",* Proceedings of 11th International Power Electronics and Motion Control Conference EPE-PEMC 2004, Riga, Latvia, September 2-4, 2004.
2. V. Chuvychin, N. Gurov, A. Skutelis *"Electric power system frequency and active power control dynamic problems",* Proceedings of 6th International Conference CONTROL OF POWER SYSTEMS '04, Strebske Pleso High Tatras, Slovak Republic, June 16-18, 2004.
3. V. Chuvychin, N. Gurov, A. Skutelis *"Optimization of the Daugava hydro power plants' control methods",* RTU scientific articles, "Energetic and electric techniques", 4 series, volume 9, publisher "RTU", Riga, 2003,70-75 p.
4. V.Chuvychin, N.Gurov, A.Skutelis, V.Strelkovs *"Dynamic's Problems of Frequency and Active Power Control in Electric Power System",* Proceedings of IEEE Bologna Power Tech 2003 Conference, University of Bologna, Bologna, Italy, June 2003.
5. V.Chuvychin, N.Gurov, A.Skutelis *"Optimization Method for Control of Hydrogenerators",* Proceedings of International Symposium MEPS 02, Wroclaw University of Technology, Wroclaw, Poland, September 2002.
6. V.Chuvychin, N.Gurov, A.Skutelis, V.Strelkovs "Plavinas HPP hydro units' mathematical modeling", RTU scientific articles, Energetic and electric techniques, series 4., volume 6., Riga 2002 (in Latvian).

Local publications:

1. Report "New technology implementation in power plant modernization and maintenance", Contract Nr.6844, 2004, (in Latvian).
2. Report "Daugava HPP cascade energetic parameters specification, to improve Daugava water resource use". Contract Nr.6707, 2003, (in Latvian).
3. Latvia Republic PATENT Nr.13053, Riga, 20.11.2003, (in Latvian).
4. V.Chuvychin, A.Skutelis "Plavinas HPP hydro units control problems", 43. student scientific and technical conference, Riga Technical University, Riga 2002, (in Latvian).
5. Report "Plavinas HPP units' operational efficiency improvement", Contract Nr.03/57-2001,2001, (in Latvian).

Structure and volume of thesis

Doctoral Thesis contains 8 chapters, conclusions and recommendations, also bibliography. Total amount is 127 pages. There are included 49 tables and 42 pictures in this work. Bibliography includes 54 used literature sources. Work includes one attachment.

1. THE DAUGAVA RIVER HYDRO POWER PLANT'S CASCADE GENERAL CHARACTERIZATION

First chapter is dedicated to the Daugava hydro power plant's cascade general characterization. The Daugava hydro power plants' cascade technical resource investigation is conducted. The features of the Daugava hydro power plants' cascade function and control basic requirements in following operation conditions are: Daugava HPP operation at frequency rise; at frequency decline; at Baltic power system, Belarus power system and associated Northwest power system isolated operation from common power system. Following questions are reviewed: Daugava HPP hydro units' allowed reactive load; Daugava HPP water reservoirs feasible constraints (water levels) and worked water speed. Daugava hydro power plants' cascade unit's control principles characterization ass well as power distribution among hydro power plants were shown. Plavinas HPP hydro unit's nominal parameters', governor type and structural scheme's detailed investigation and analyses were done.

Joint Stock Company "Latvenergo" branch "Daugava hydro power plants" henceforward in text Daugava HPP, includes three hydro power plants: Plavinas HPP, Kegums HPP and Riga HPP, which are located Daugava river downstream (Fig. 1.1). Total installed power is 1534 MW. Daugava HPP can generate approximately 70% from all Latvenergo generated electric power amount (it depends on annual climatic conditions). Hydro power plant cascade is designed and established, to rational use of Daugava water resource energy.

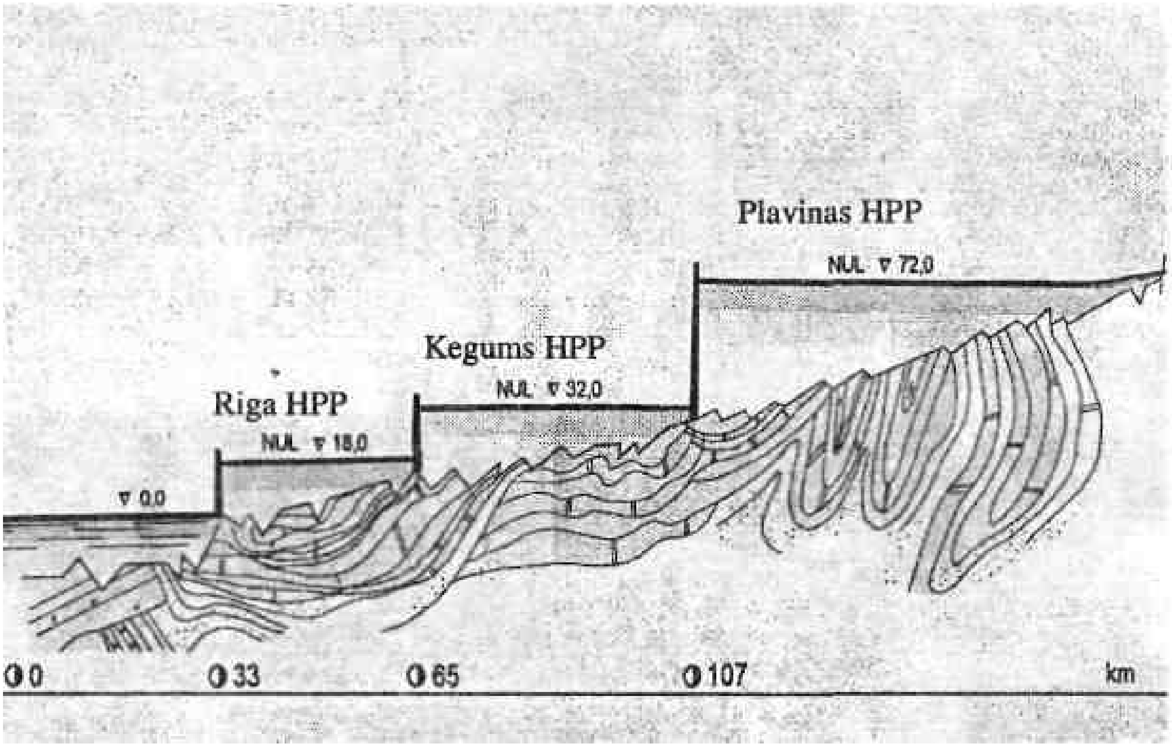

Fig. 1.1. Location of the Daugava hydro power plants

There are 10 hydro units in service at Plavinas HPP, which are equipped with Francis type of turbines. Total installed power is 870 MW (after unit A2, A8 reconstruction in 2001). Water flow through the turbine at calculated water head is in range 279 - 290 m^3/s. Water head value can vary from 35 to 41 meters. Generators are connected in blocks with 330 kV transformers.

There are 4 hydro units in Kegums HPP-1 with total 74 MW power capacities. Calculated water head - 13,5 meters. Generators are connected in block with 110 kV transformer. In 2001 there were plant reconstruction (4 hydro units reconstructed) replacing by new 5 blades Kaplan type turbine. Water flow through turbine Kegums HPP-1 at calculated head is in rage 138 - 145 m^3/s.

There are 3 hydro units in Kegums HPP-2 with total installed power 192 MW (each 64 MW). Water flow through turbine Kegums HPP-2 at calculated head is 540 m^3/s. Calculated water head is - 14 meters. Hydro units are connected in block with 110 kV transformer.

There are installed 6 Kaplan type hydro units in Riga HPP with total power 402 MW. Water flow through turbine at calculated head is 607 m^3/s. Calculated water head is - 12,9 meters.

Normal hydro units' **operational condition** control is realized with respect to hydro unit nominal power value. After generating mode start command is received, unit automatically picks up nominal power and generates this power value until stop command will be received. In normal operational mode hydro power stations control realizes considering the Daugava HPP water reservoirs allowed level and speed of water flow values.

Besides usual hydro unit operational mode there are possible also **emergency modes**. To provide stable power system operation in emergency modes, for Daugava hydro power stations there are defined control basic requirements following emergency modes:

- Power generation at load peak period;
- Power system emergency reserve;
- Power system frequency control;
- Power system voltage control.

Investigations mainly consider normal Daugava HPP plants hydro units' operational mode, though the above-mentioned emergency operation modes are interesting too. Emergency operation modes apply restrictions to active power generation process. These problems also will be considered in this work.

To decrease hydro power plant negative influence on environment, there are defined allowed minimal plant's water reservoir levels and maximal water flow speed respectively apiece year time period. To each of the hydro power plants there are defined water reservoir maximal level ***constraints:*** Riga HPP 18 m (above sea level); Kegums HPP 32 m and Plavinas HPP 72.70 m.

Daugava HPP hydro power plant units' control realizes as follows: DC Baltija dispatchers - Latvenergo Central Dispatch Department (LE CDD) dispatchers - HPP on duty dispatchers. Practically DC Baltija dispatchers give command to LE CDC dispatchers, who further create control commands directly to autooperator. Commands include: how many hydro units' must be started, stopped, transferred to synchronous compensator (SC), or transferred from SC to synchronous generator (SG).

Power distribution between hydro power plants' gets calculated in annual plans considering water flow forecasts. Annual plans get developed in DC Baltija power system department. Plans get produced in previous year-end and every month get corrections following the real situation. DC Baltija dispatchers every day provided with twenty-four hours plan of power distribution between power plants.

Power distribution between power plants is discrete - accordingly hydro power plants installed units nominal (rated) power values. Besides each hydro power plant water pass-capability, water reservoir capacity and water level constraints are taken into consideration.

Disadvantages of existent hydro units control principles.

Plavinas HPP hydro units optimal operational mode corresponds to one calculated (passport) water head value. During hydro unit operation water head value changes in range from 35 m to 41 m. If head value changes, then hydro unit output power value also should be changed, to reach maximal hydro unit efficiency factor. Now unit's generated power value is constant for any head value and units all time are operating with nominal output power, that increase generation required water amount.

At the Kegums HPP-1 for determination of water head value use only one sensor in plants downstream and one in upstream, it means, that all four hydro units are optimized only after one water head measurement. Real water head value of each hydro unit's turbine differs, it depends on: how many and in what order at this moment hydro units operate.

Kegums HPP-2 turbine blades are whipped, wherewith also schemer is switched off. That is the reason, why hydro units optimization gets reduced to unit optimal operation at one water head value with one concrete output power value. Real water head value changes, respectively generator generated power value should be changed accordingly to the optimal power value corresponding to real water head.

Riga HPP has stepped first step to implement optimization, in 2005 there were restored device, which makes power correction according to the water head value. Wherewith there is provided possibility to optimize Riga HPP accordingly to head and to implement new optimal control methods. Second step in plants optimization is to implement new optimal control methods.

2. REVIEW OF EXISTING METHODS FOR POWER SYSTEM CONTROL OPTIMIZATION

Second chapter is dedicated to review existing power system control optimization methods. Review of mathematical modeling and optimal control basic methods was done. Reviewed following power system optimization methods: power system with dominant hydro energetic structure; one river hydro power plants cascade control optimization: power system control optimization, which consists from hydro and steam power plants. Survey of existing analyses methods for a different hydro power plant units' mode is done.

Mathematical model can be described as an equations' system, that bond manufacturing process parameters, input and output parameters with other parameters and constraints. Any technological processes' full mathematical model includes five equation groups.

1. *Effectiveness equation* (objective function). Shows conformity stage for one or another given control objective solution. In probability form it can be written as:

$$MF(Y, X_v, X_{nv}) \Rightarrow \max, \qquad (2.1)$$

Where M - mathematical possibility symbol (do not write if effectiveness equation has determinate form);

F - objective function;

Y- output parameters;

X_y - controllable input parameters;

X_{nv} - uncontrollable input parameters.

2. *Relationship equations.* Describes system technological process and shows system output parameter dependence from the other condition controllable parameters

$$Y = A(X_v, X_{nv}) \text{ vai } Y=A(X) \qquad (2.2)$$

This relationship sometimes is called element or manufacturing characteristic. Characteristic - is relationship totality, what sets manufacturing outputs *Y* corresponding with inputs *X*. Objects, to who input come signal *X(t)* and from output come variable *Y(t)*, characteristic is operator *A*. Operator shows *Y(t)* acquiring procedure sequence and content, after given *X(t)*. In genera! case operator *A* characterize input consumption on one output item, as well as input scoop (preclusion) anent to output. Characteristics can obtain theoretically on this basis special measurements or direct identification, those can be written in covert way:

$$A'(X,Y)=0.$$

That notation, very often is used at object behaviour theoretical analyses.

If object characteristic does not changes in a time, then object considers as stationary. Due to ageing and other reason, object characteristics changes along the time. Practically object majority are not stationary. For them evolve (if it is possible) time to plan such length, that object can consider as a stationary. No stationary consideration sorely complicates mathematical modeling.

3. *Constraints equations.* These equations show system input and output parameter allowed changes limits, technological processes progress conditions. Constraints can be in equation (balance type constraints) and in inequality form (parameter changes limit constraints). In general constraint can be written as:

$$F_{ier,\, i}\,(X,\, Y) \le A_{ier\ i}. \qquad (2.3)$$

By form *F.* constraints function can be linear or nonlinear. That can be written in determinate or probability form. Constraints often write in parameters allowed change diapason form. That input (controllable) parameters constraints in determinate viewpoint can write in following way:

$$X_{i,v,min} \le X_{i,v} \le X_{i,v,max} \qquad (2.4)$$

As an organizing system constraints cannot be technological constraints, but directive guidelines (work plan), which have the law force and must be executed.

4. *Optimal control equations* or optimization equations. These equations are optimization main result. Control equation is some function, which shows optimal relevance system controllable parameters from objective, system output and its uncontrollable parameters:

$$X_{v,o} = f_v\,(F,\, Y,\, X_{nv}\,). \qquad (2.5)$$

Determination of control rule is system behavior optimization last stage. Optimization methods are used for determination of control rules.

5. *Adaptation equations.* In general case automatic control system is adaptive system with conform abilities. With adaptation we realize parameters, system structure and control influence change process, basing on running information, with aim to reach stated, usually optimal system state, at initially uncertainty and changes in system work conditions. In

unhidden way it can be written as observed system operation economical condition and at given time period existent, difference minimization:

$$E_0\,(X, Y) - E\,(X_1, Y_1) \Rightarrow \min, \qquad (2.6)$$

where E_0 - best achieved effect at conditions, which are close to existent inner conditions.

Power system control is complicated and a multi criteria task. Power system optimal control main task is related with such power system incorporation calculation and implementation, at that will be provided necessary frequency and voltage values on consumer sub-stations bus bars and will be acquired great economy at electric and thermo power generation and distribution.

Solution of power system optimal control problems depends on power system structure. Since united power system control system is hierarchic, then optimization tasks, at every level are different. Minimization function at each hierarchy level can be different.

This research deals with power distribution optimization problem of the Daugava HPP cascade hydro units. Power distribution optimization problem between JSC "Latvenergo" system plants is not considered. **Daugava HPP cascade hydro units summary load power is assumed as defined and the task is to manage load power distribution between separate cascade hydro units optimization.**

Optimization mathematical model is defined by optimization criterion. An optimization criterion in this work is plant hydro units' water consumption minimum.

$$F = \sum_{i=1}^{n} Q_i\,(P_{Gi}) \to \min \qquad (2.7)$$

where $Q(P_{Gi})$ - consumption characteristic, which displays relative energy resource consumption during one hour in plant i.

In general case unit water consumption depends on many variables and objective function can be expressed:

$$F = \sum_{i=1}^{n} q(P_{GAi}, l_{AB}, l_{LB}, Q_i, f, s, \alpha) \to \min \qquad (2.8)$$

where: q - relative water consumption;

P_{GAi} - generated active power for generator i;

l_{AB} - plants upstream level;

l_{LB} - plants downstream level;

Q_i - water flow for generator *i;*

f- frequency;

s - droop;

a - turbine blade angle (only for Kaplan type turbine).

Constraint equations bonds many parameters, for example:

1) Power balance. All cascade power plants summary power should be equal to at given moment defined load power P_{uzd}

$$\sum_{i=1}^{n} P_i - P_{uzd} = 0 \qquad (2.9)$$

2) Inequalities.

- Plants water levels constraints:

$$l_{AB,\min} < l_{AB} < l_{AB,max},$$

$$l_{LB,\min} < l_{LB} < l_{LB,max}$$

- Units power limits:

$$P_{i,min} < P_i < P_{i,max}$$

- To units defined primary frequency control reserve, which can be expressed with power correction by frequency equation:

$$\Delta f - s_i \Delta P_i = 0,$$

where s_i – generator *i* droop,

Δf - system frequency deviation from nominal value ($\Delta f = f_0 — f$).

Hydro power plant units' optimal control mode determination problem always was actual, especially at short term planning, which gives notable economic effect. Publications list only for last ten years testifies about the interest of this theme.

Optimization aim changes depending on power system structure, as an examples can mention:

- One power plant on river;
- Power plant cascade on one river;
- Power plants on one river branches;

- Power system, with dominant hydro power plants;
- Power system with hydro and steam power plants.

At each optimization stage there is defined objective function, which can be different for each optimization approach. Usually objective function consists of many parameters that mainly are not linear.

3. HYDRO UNIT TURBINE'S MODELLING METHOD

Third chapter is dedicated to hydro units' turbine modeling method developing. Characterization of hydro units turbine model characteristics and generation experimental characteristics where done. Inspection of possibility to apply characteristics for operation analyses where done.

Complicated power system mathematical description is very complex that is why physical modeling methods are used, which as a result gives turbine energetic characteristics. This method was used to analyze Daugava HPP hydro units' operational modes.

Many parameters characterize hydro units' operational modes. Some of the main parameters are wicked gates opening, water flow, water head, turbine blade angle (Kaplan turbines), turbine power, generator power, efficiency coefficient etc. Majority of these parameters are displayed in hydro units' model and generating experimental characteristics.

For every hydro unit and turbine parameters such as: efficiency coefficient, water consumption, optimal mode etc. parameters values can be expressed from operational characteristics. There are two types of operation characteristics:

1) characteristics, which are obtained as a result of turbine model investigations, or model characteristics;
2) characteristics, which for hydro unit are obtained in experimental way on site in plant, or generation experimental characteristic.

Hydro units' turbine model characteristics or operational characteristics usually are obtained in specialized laboratories or in manufacturing factories using certain model investigation methods.

Approximately fifteen hydro unit characteristics families are known, however in operation mainly three types of characteristics are used. These characteristics were obtained from ***hydro units' generation operational characteristics,*** which were created for each hydro unit at on site verification in 1968 and 1969.

Operational characteristics, $\eta_{HA} = f\,(H, P_{HA})$,

where η_{HA} - hydro unit efficiency coefficient;

H - water head;

P_{HA} - generator power.

Water consumption characteristics, $Q = f(P_{HA})$,

where Q - water flow through a turbine.

These characteristics usually get constructed at various constant water heads.

At present situation above inspected characteristics in hydro units operation serves only as informative material, because hydro units control provides nominal power setting. In case there is a start command to start hydro unit in generator mode, then it automatically reaches the nominal power setting and operates with this setting until stop command.

After hydro units operational characteristics analyses in this chapter, we can conclude, that ***at the hydro units nominal power values, efficiency coefficient values is not optimal,*** besides, that changes, if water head values are changing. Wherewith it is necessary to make detailed characteristics processing and analyses, to propose hydro units operational mode optimization algorithm. The next sections are devoted to survey of motioned above questions.

4. PLAVINAS HPP HYDRO UNIT OPERATING OPTIMIZATION ALGORITM

Fourth chapter is dedicated to synthesis of Plavinas HPP hydro units operational modes optimization algorithm. Determination of hydro units' operational effectiveness criteria and hydro units' operational mode optimization object function are presented. A characteristics processing during the optimization process, or characteristics modeling was done. Hydro units' optimal operational mode determination algorithm synthesis was done, algorithm was acknowledged as a Latvia Republic patent. Algorithm's adaptive scheme for hydro unit optimal operational mode determination was developed.

The main optimization objective in this research is to provide hydro units operation with minimal relative water consumption $[m^3/kWh]$, or to provide operation with best effectiveness coefficient, which is the main optimization criterion. To provide optimal operation mode, it is necessary to have precise water flow measurements, which difficult to arrange in real time. There are problems with water head measurements. Usually these measurements do not fulfill at each hydro unit that cause mistakes in optimization algorithms.

Hydro units power depends on turbine wicket gates opening stage. Water head changes at constant wicket gates opening causes turbine power changes. For the same upstream water level turbine power changes depending on the number units in operation, due to changes of downstream water level, what respectively change water head value.

Unit operation efficiency means use of each unit in mode with minimal relative water consumption, which corresponds hydro units' maximal efficiency coefficient. Relative water consumption q, [m^3 / *kWh*] is determined using following formula:

$$q = \frac{Q}{P_G} * 3600, \tag{4.1}$$

Where Q - water flow in turbine, m^3/sek;

P_G - generator power, *kW*.

In general case relative water consumption depends on water head H, water flow Q and generator output power P_G :

$$q=f(H,Q, P_G). \tag{4.2}$$

where q - relative water consumption, m^3/kWh;

H - water head, m;

Hydro power plants units use with minimal relative water consumption most of the time will give notable economic effect. Respectively ***optimization objective function*** will be:

$$f_{opt} = \min q, \text{ or considering (4.2)} \tag{4.3}$$

$$f_{opt} = \min f(H,Q,P_G, l_{AB}, l_{LB}) \tag{4.4}$$

where l_{AB} , l_{LB} - respectively upstream un downstream water levels, *m*.

Given objective function is simplified comparison to theoretical, leaving for practical objective function leaving only determinative parameters.

So, hydro unit optimal mode depends on water head H (non controllable parameter), water flow Q (controllable parameter) and generator output power P_G. (controllable parameter). During hydro unit operation these parameters changes and, for example, at new H

value optimal mode will be different, or, in other words, minimal relative water consumption, or maximal effectiveness coefficient (controllable parameters) will be for another power P_G value (see Fig. 4.1., 4.2. and 4.3.).

To provide hydro unit optimal mode, it is necessary information about water head *H,* water flow *Q,* real and optimal relative water consumption *q.*

To realize optimal control it is necessary to provide precise parameters' Q, P_G and H measurements, what using existent methods and devices is difficult to ensure. For example, standard wattmeter with relatively high accuracy class 0,2 is not suitable for measurement of generator output power, because mentioned accuracy that provides only at sine curve input values and static mode. Due to water flow irregularity, power value is continuously variable and device indications are unstable. Hydro power plants upstream level measurements are taken at two points near the dam, not at the each unit and that gives the notable error in *H* measurements. Turbine water flow *Q* measurements because of complexity are not carried out.

New *optimal operational mode determination method is proposed, which parameters Q and H determine indirectly using hydro unit model load characteristics.* Each unit is provided with model characteristics families, which show hydro unit turbine power P_T dependence from water flow *Q* at different water heads *H* and power P_T dependence from servomotor position *S* also at different water heads *H.* Below investigations will be described of this proposed optimization method, which basically is *semi-graphical method,* where semi-graphical technique is used.

New characteristic families were developed, to create hydro power plants optimal operation algorithm. During the analyses there were *not* processed existent hydro units *generation experimental characteristics,* for further optimization process, in characteristics processing *were* used hydro units *turbine model characteristics,* or turbine operational characteristics, which are obtained in specialized laboratories.

From turbine operational characteristics, is possible to calculate necessary optimization characteristics using formula:

$$P_T = 9{,}81 * Q * H * \eta_{HA}, \qquad (4.5)$$

where P_T - turbine power, kW;

η_{HA} - hydro units efficiency coefficient.

$$\eta_{HA}=\eta_T * \eta_G \, , \tag{4.6}$$

where η_T - turbine efficiency coefficient;

η_G - generator efficiency coefficient.

As a result of analyses there were developed new characteristics families. Fig. 4.1.- 4.3. illustrates the examples of: Plavinas HPP old generation hydro units turbine operation characteristics; turbine water consumption characteristics and turbine relative water consumption characteristics.

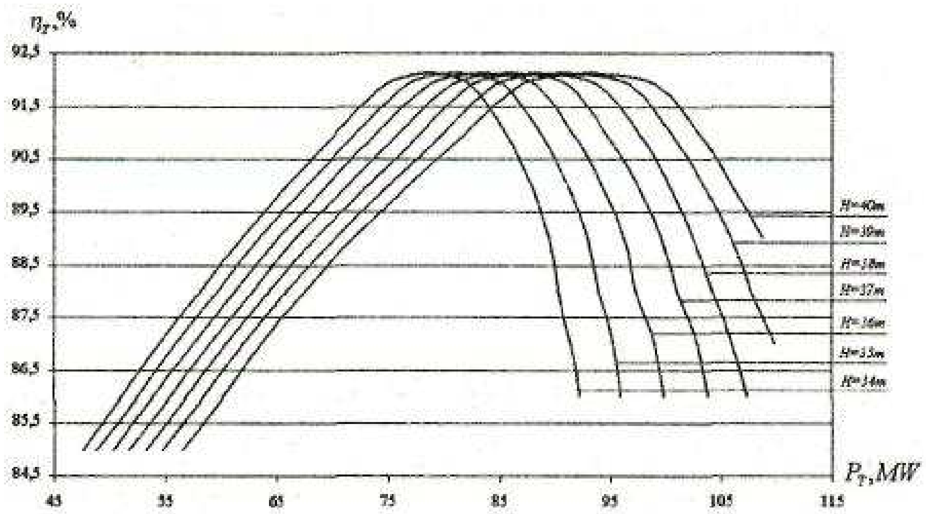

Fig. 4.1. Old generation units' turbine operational characteristics

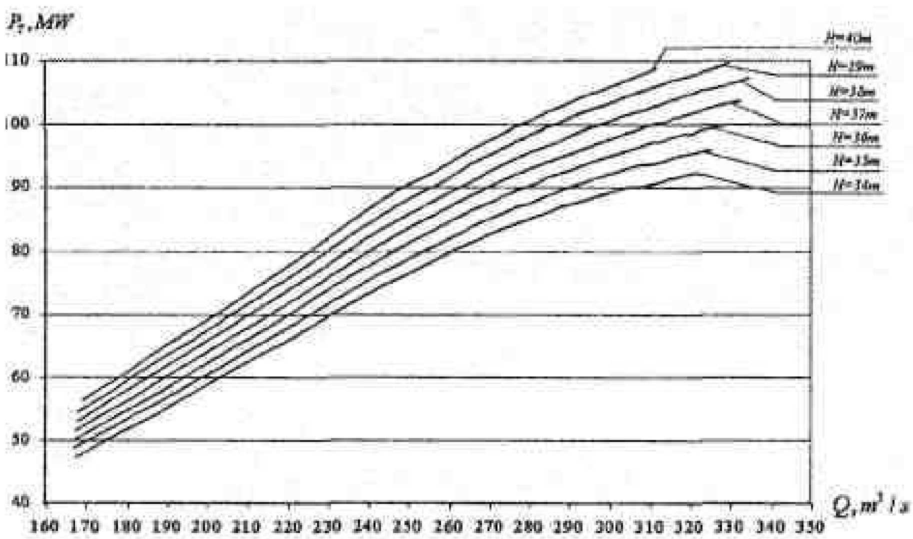

Fig. 4.2. Old generation units' turbine water consumption characteristics

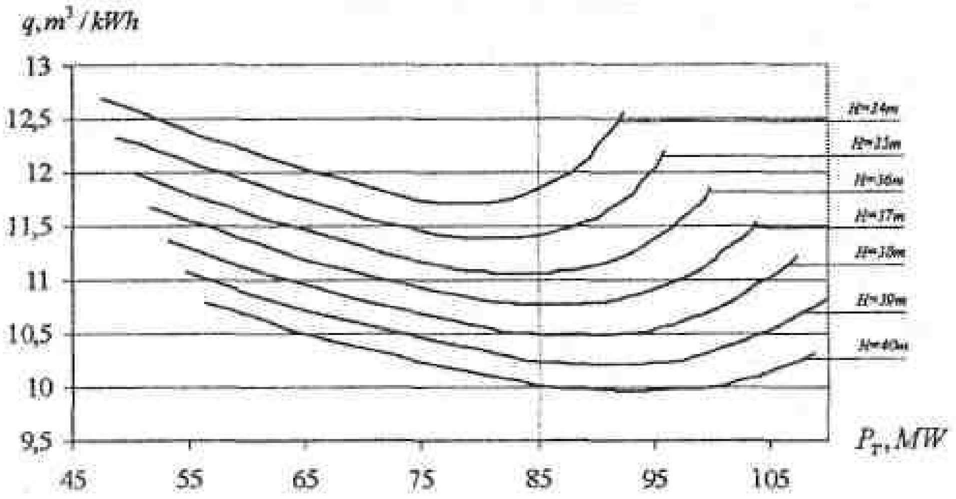

Fig. 4.3. Old generation units' turbine relative water consumption at different water head values

From Fig. 4.3. we can see, that if water head value changes, then changes turbine power value, which corresponds to q_{min}. Fig.4.4. displays obtained Plavinas HPP modernized ***hydro unit turbine optimal mode characteristics***, or characteristics - turbine optimal power as a function from water head $P_T = f(H)$, which were constructed taking into consideration for q_{min} optimal power value P_{opt}, at corresponding water head (see Fig.4.3.).

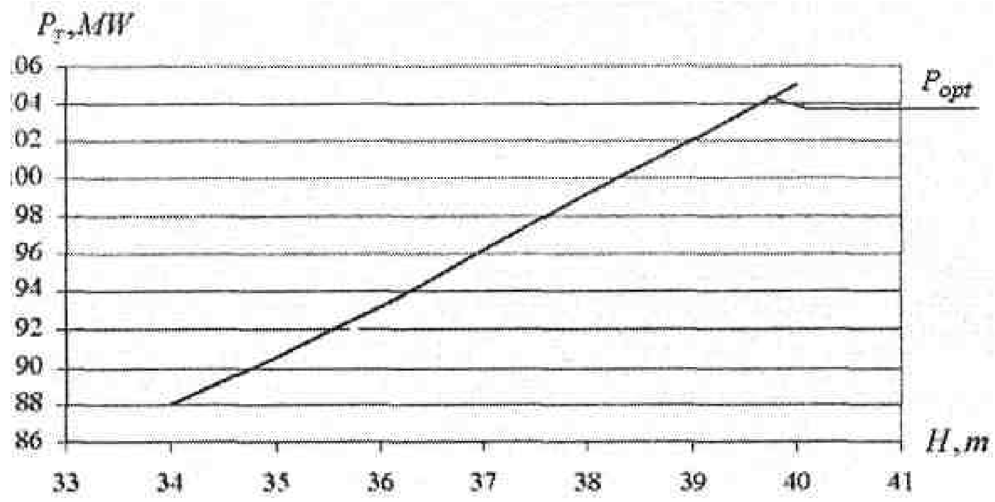

Fig.4.4. Reconstructed hydro units turbine optimal mode characteristic

Turbine model characteristics were transformed for practical use in convenient form, using semi-graphical method. Proposed characteristics (families) new form is convenient for mathematical processing (characteristic are available in electronic tables form), to use in further turbine regulator modernization.

As it was mentioned before, there are not possibilities for precise measurements of water flow and there are problems with water head measurements. Knowing real water head minimizes optimization errors. During the investigations, there where developed method to determine real water head.

Study of plant hydro units technical potentiality analyses, showed, that it is possible to measure following values:

- generator power: $\boldsymbol{P_G}$***, MW,***
- hydro units' wicket gates servomotors position: ***S, mm.***

From above mentioned, hydro units' turbine model characteristics were processed and analyzed with aim to get characteristics families - hydro unit generator power as a function from servo motor opening $\boldsymbol{P_G=f(S)}$, at each water head value (Hl...Hn), see Fig.4.5.

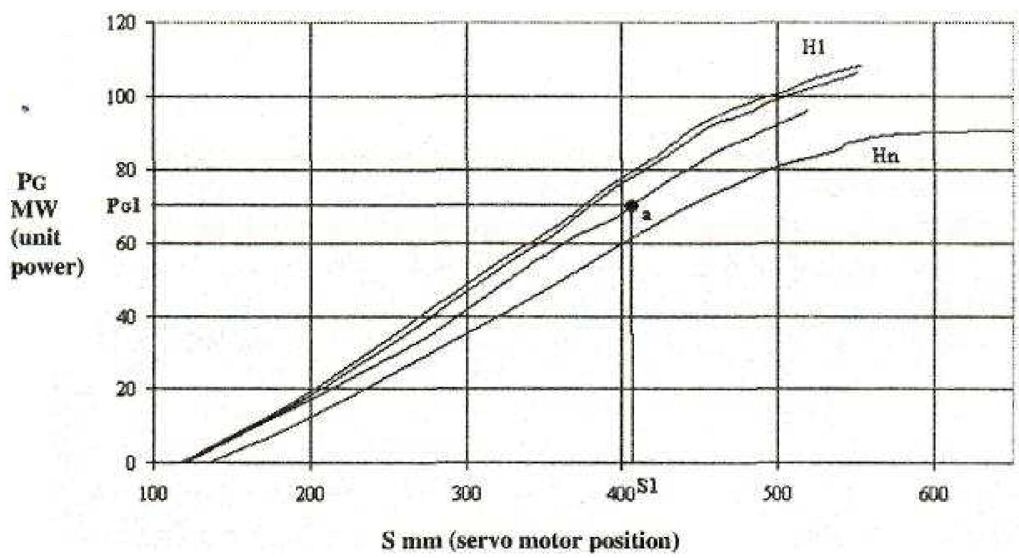

Fig.4.5. Hydro unit characteristics $P_G = f(S)$ family

From acquired characteristic family $P_G = f(S)$ - hydro units as a function from servo motor opening, at corresponding water head, after hydro unit power P_{G1} and servo motor position S_1 measurements, it is possible to determine real water head ***H, m*** on turbine (point „a" in Fig.4.5.).

Taking into account mentioned above optimal mode determination problems and real optimization possibilities analyses, and also carrying out hydro unit turbine model characteristics processing and analyses, there is proposed new operational optimal mode determination algorithm for Plavinas hydro power plants units. Plavinas hydro power plant's unit operational optimal mode determination algorithm is demonstrated in Fig.4.6.

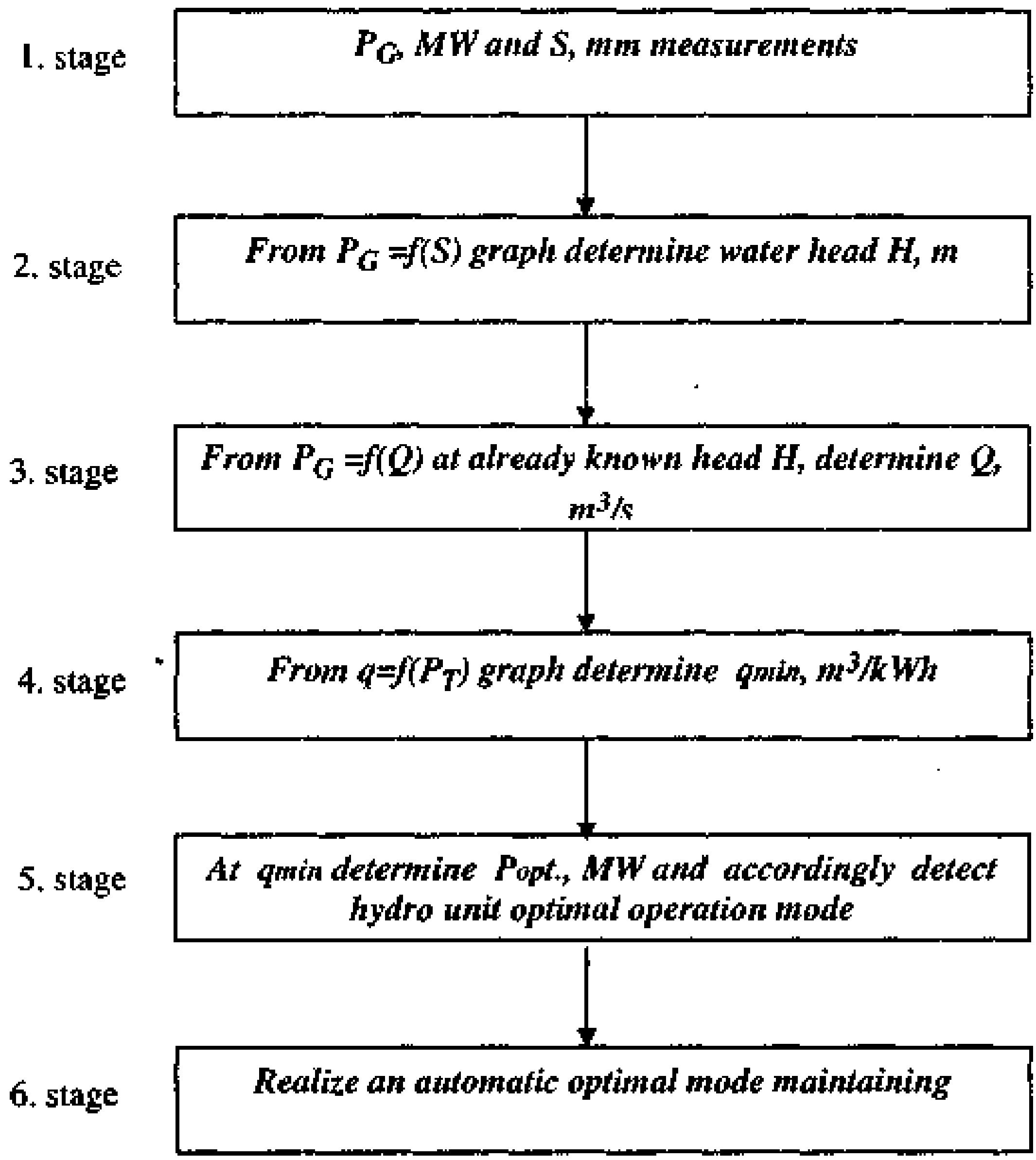

Fig.4.6. Plavinas hydro power plant's unit optimal operation mode determination algorithm

Detailed description of Plavinas HPP hydro unit's optimal operational mode algorithm action stages is shown in promotion work.

Plavinas HPP hydro units' optimal operation mode determination algorithm action stages adaptive scheme is demonstrated in Fig. 4.7.

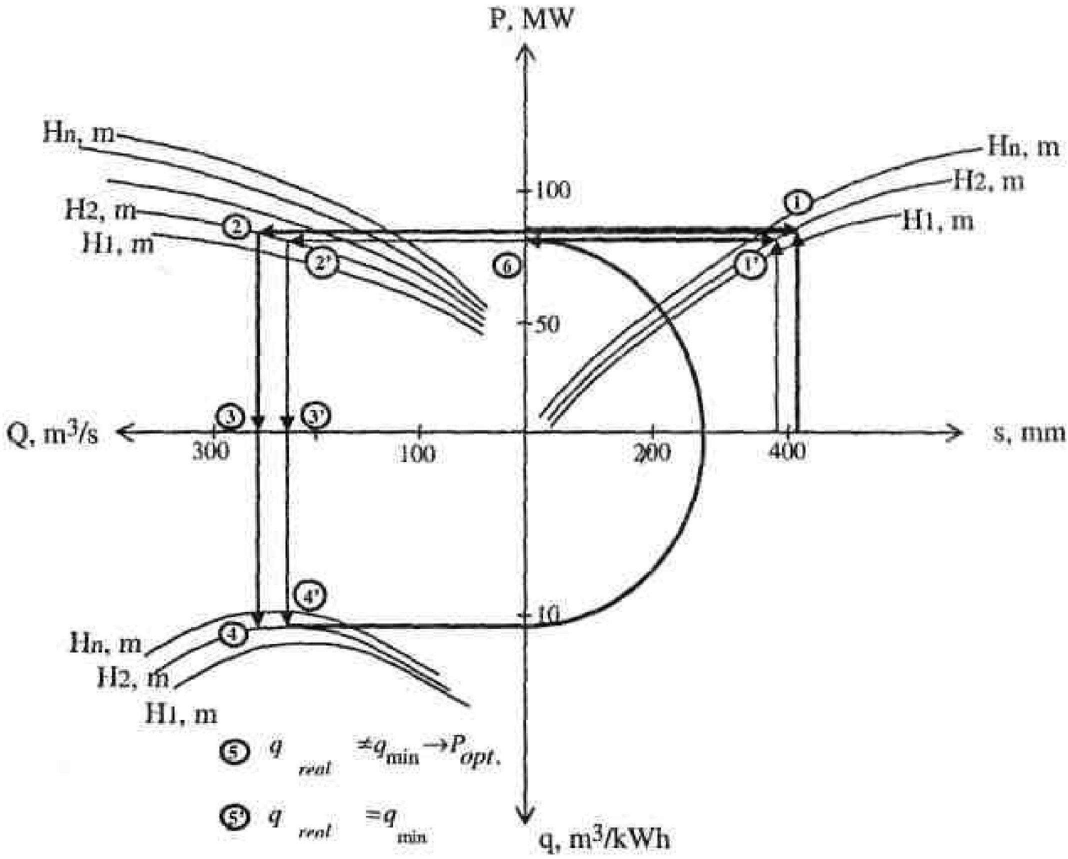

Fig. 4.7. Hydro units' optimal operational mode determination adaptive scheme of algorithm stages.

5. OPTIMAL OPERTIONAL MODE'S DETERMINATION ANALYSES

Fifth chapter is dedicated to optimal operational modes determination analyses. Plavinas HPP optimal mode analyses and Riga HPP optimal control possibility analyses were done.

One of the work's activity deals with analyses how hydro units' output power variations influence the hydro units' efficiency coefficient, at defined water head values. Plavinas HPP hydro units' model characteristics where processing with aim to acquire characteristics family: hydro units efficiency coefficient as a function from hydro units power $\eta_{HA} = f(P_{HA})$.

Following model characteristic families were used during the processing:

1) Old generation units - PO 984-B-600 type turbine universal operational characteristic No.2189-135;
2) Modernized units - PO 45/3232 type turbine universal operational characteristic No.2697;
3) Reconstructed units - Plavinas HPP Prototype Hill Diagram, APP. 75.

Optimal operational points, considering water head value (H, m), were obtained from turbine operational characteristics for old, modernized and reconstructed hydro units. These values are presented in Table 5.1.

Table 5.1.

Old modernized and reconstructed hydro units optimal operation points

	Old generation units	Modernized units	Reconstructed units
H, m	Popt.HA, MW	Popt.HA, MW	Popt.HA, MW
40	89,99	102,69	90,79
39	87,75	99,76	91,16
38	85,41	97,02	88,75
37	83,36	93,89	84,18
36	81,12	91,35	81,98
35	78,88	88,70	80,09
34	76,44	86,06	78,40

To provide hydro units optimal operation mode, hydro unit governor scheme should be supplemented with optimization device, which should operate using proposed by authors Plavinas HPP hydro units optimal control algorithm, which where described in fourth chapter, and to provide optimal power values at corresponding water head.

As a result of analyses, new Riga HPP hydro units optimal control algorithm was developed, which considers all above mentioned problems. Riga HPP hydro units optimal control algorithm *does not* particularly observed in these investigations.

6. ANALYSES POSSIBILITY OF PLAVINAS HPP HYDRO UNIT PARTICIPATION IN FREQUENCY REGULATION, CONSIDERING OPTIMIZATION CONDITIONS

The sixth chapter is dedicated to analyses possibility of Plavinas HPP hydro units participation in frequency control, considering optimization conditions. Plavinas HPP hydro units operation analyses at power variations, if a hydro unit operates in optimal mode.

One of the power system load schedule planning steps is active power reserves planning.

To compensate planned inaccuracy in power system twenty-four hours load, scheduled reserve should be more than 3% from planned maximal power system power.

There are such kind of reserves:

a) operative reserves (instantaneous, fast and slow):

Instantaneous reserve - amount depends on a turbine primary governor droop value and boiler type;

Fast reserve - realizes automatically on hydro units start procedure (up to 3 minutes);

Slow reserve - realizes in 30 minutes time period, when dispatcher schedule generation units pick-ups load accordingly transmission system operator insuuction. This reserve includes also user load restriction or disconnection.

b) Cold reserve - reserve, which degree and realization time depends on equipment start characteristics and that operational status. These reserves are user load restriction or switch off.

Power system reserves are realized in this way:

a) operative instantaneous reserve - at frequency changes;

b) operative fast reserve - when power system high-powered generator switches off, transit line overloads or load reaches stability limit;

c) operative slow and cold reserve - when generation or consumption changes.

At frequency control case, for each power plant hydro unit should be defined active power "+" diapason (active power increase) and "-" diapason (active power decrease) depending on frequency conditions. Plavinas hydro power plant is an object for investigation, because it has been selected to frequency control according to Latvia Power system basic-requirements (see "Network Codex" 4. chapter), and also, because optimization of this plant will give larger economic effect.

Turbine universal operational characteristics determine minimal and maximal power limits. Minimal calculated water head H=34m determines turbine power minimal limits but hydro unit generator nominal power values determine maximal limits. Minimal and maximal power constraints should be taken into account at possible plant hydro units' participation in primary frequency control.

This chapter's another task was to display how changes hydro units water flow Q, m^3 /sec and corresponding relative water consumption q, m^3 /*kWh* values, if unit is used out for frequency control with power reserve regulation possibilities -5MW and -10 MW. As an example, in table 6.1. following values are displayed: turbine power P_T, turbine efficiency coefficient η_T, water flow Q and relative water consumption q, at water head values 40m, 39m, 38m, 37m, 36m, 35m and 34m. Power change from calculated turbine optimal mode is -5 MW and -10MW.

Table 6.1.

Results of the old generation hydro unit characteristic analyses

	H = 40 m				H = 39 m			
Change, MW	P_T, MW	η_T, %	Q, m^3/sec	q, m^3/kWh	P_T, MW	η_T, %	Q, m^3/sec	q, m^3/kWh
Optimal mode	92.30	0.92	255.67	10.23	90.00	0.92	255.69	10.49
- 5	87.17	0.91	244.11	10.34	84.87	0.91	243.77	10.61
- 10	82.04	0.91	229.75	10.34	79.74	0.90	231.59	10.72

Examining the results, which are displayed in Table 6.1., can conclude, that ***power change*** -5MW and -10MW ***from optimal mode***, in this case at H=40m is 92.30 MW with relative water consumption value 10,23 m^3 /*kWh, increase relative water consumption* ***value*** up to l0,34 m^3 /*kWh.* ***This conclusion should be taken into account, at economical calculations, which should be carried out, examining two possible cascade operational modes: optimal operation mode and participation in frequency control. Participation in frequency control reduces cascade optimal operation mode total effect.***

7. THE DAUGAVA HPP AUTOMATIC OPTIMAL CONTROL SYSTEM SCHEME

Seventh chapter is dedicated to development of the Daugava HPP cascade automatic optimal control system scheme. Daugava HPP cascade hydro units real operation mode parameters statistic investigations and analyses were done using developed hydro units operational mode optimization method. Automatic optimal control system scheme description and Daugava HPP cascade given power optimal distribution algorithm were given. Daugava HPP cascade given power optimal distribution algorithm logical scheme and automatic optimal control system scheme were developed.

To propose the Daugava HPP cascade joint automatic optimal control scheme and to manage plant operational mode optimization analyses, there were handled detailed Plavinas HPP hydro units' existent operational modes statistic data analyses and investigation. It is difficult to forecast the water inflow in a long time period that is why in hydro units operational mode optimization should be guided analyzing real situation.

As it was mentioned before, now it is given discrete power distribution among hydro power plants, or corresponding to hydro power plants installed hydro units nominal power values.

For proposed optimization method, then every hour (time interval is assumed, to simplify calculation process) in Plavinas hydro power plant appears total power $P_{opt.}$-P_{real} difference $\Sigma\Delta P$ [MWh] surplus or deficit (see Fig. 7.1.).

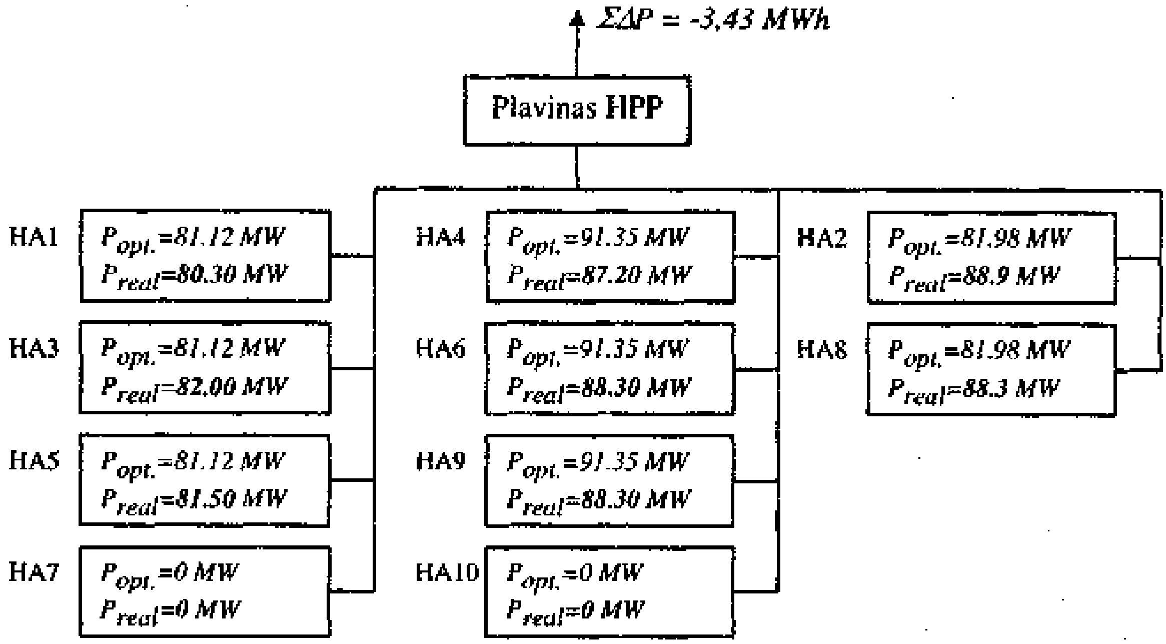

Fig. 7.1. Plavinas HPP optimization analyses, using spring maximum data 04.03.2002, time 8.00 a.m. to 9.00 a.m.

From an example in Fig. 7.1, follows, that if Plavinas HPP 04.03.2002 would operated in optimal mode, then plant should generate generated in time period from 8.00 a.m. to 9.00 a.m. about 3,34 MWh less as it where generated real - operating accordingly hydro power plants installed hydro units nominal power values. Wherewith, to secure demanded total generated electric power load from cascade, this 3,34 MWh power value should be in addition generated in other cascade plants: Riga HPP or Kegums HPP1 or Kegums HPP2.

As a result of analyses, for example, there were obtained $\sum\Delta P$ [MWh] values for each hour, each day and each 2002 March, August and 2003 November first week in total -practically that was a megawatt hours, which were generated in *non optimal* mode.

Chapter describes optimization controller realizing operation algorithm and assumed *requirements.* Algorithm was founded, which realizes optimal power distribution between plants, after Plavinas HPP optimization is managed, and also algorithm foresees water reservoirs levels defined constraint at this power distribution.

1.Optimal power distribution between plants *first requirement* - equal water flow, via each power plant.

$$Q_{PHPP} = Q_{KHPP} = Q_{RHPP} \quad (7.1)$$

2.Total power value for cascade P_{lmcak} is known, because is given.

3.Equation (7.1) can be rewritten in following way:

$$\frac{P_{PHPP}}{g * H_{PHPP} * \eta_{PHPP}} = \frac{P_{KHPP}}{g * H_{KHPP} * \eta_{KHPP}} = \frac{P_{RHPP}}{g * H_{RHPP} * \eta_{RHPP}}, \quad (7.2)$$

where P_{PHPP}, P_{KHPr}, P_{KHPP} - Plavinas, Kegums, Riga hydro power plant power, kW;

g = 9,81;

H - water head corresponding plant;

η_{PHES}, η_{KHES}, η_{RHES} - corresponding hydro power plant efficiency coefficients.

4.Cascade power value is equal to all plants' power sum:

$$P_{cascade} = P_{PHPP} + P_{KHPP} + H_{RHPP} \quad (7.3)$$

5.Water heads values H_{PHPP}, H_{KHPP}, H_{RHPP} for each plant are known from plants upstream and downstream levels measurements.

6. Assumed, that plants efficiency coefficients are equal ($\eta_{PHPP} = \eta_{KHPP} = \eta_{RHPP}$). Their diapason is η = 0,93 + 0,97 and for this kind of calculation that assumption is acceptable, because further optimization process this assumption essentially not influences.

7.Then equation (7.2) can be rewritten as:

$$\frac{P_{PHPP}}{H_{PHPP}} = \frac{P_{KHPP}}{H_{KHPP}} = \frac{P_{RHPP}}{H_{RHPPS}} \quad (7.4)$$

8. If we know water head values, then we can implement following signs:

$$\frac{1}{H_{PHPP}} = a, \quad \frac{1}{H_{KHPP}} = b, \quad \frac{1}{H_{RHPP}} = c,$$

then equation (7.4) can be expressed as:

$$a * P_{PHES} = b * P_{KHES} = c * P_{RHES} \quad (7.5)$$

9. *The second requirement* for optimal power distribution between plants- all plant total power should be equal with demanded power value.

$$P_{PHPP} + P_{KHPP} + P_{RHPP} = P_{demanded} \quad (7.6)$$

10. From (7.5) can express power P_{KHPP}, P_{RHPP} via P_{PHPP} value, because P_{PHPP} in optimization process is determinative plant, and other plants should compensate demanded and optimal modes power difference:

$$P_{KHPP} = P_{PHPP}\frac{a}{b}; \quad P_{RHPP} = P_{PHPP}\frac{a}{c}; \quad \text{where } \frac{a}{b} \text{ and } \frac{a}{c} \text{ are known} \tag{7.7}$$

11. Inserting in (7.6) values from (7.7) acquiring:

$$P_{PHPP} + P_{PHPP} * \frac{a}{b} + P_{PHPP}\frac{a}{c} = P_{demanded}$$

$$P_{PHPP}\left(1+\frac{a}{b}+\frac{a}{c}\right) = P_{demanded} \tag{7.8}$$

12. From equations (7.8) determine P_{PHPP} :

$$P_{PHPP} = \frac{P_{demanded}}{\left(1+\frac{a}{b}+\frac{a}{c}\right)} \tag{7.9}$$

13. From (7.7) and (7.9) determine P_{RHPP}, P_{KI} :

$$P_{RHPP} = P_{PHPP}\frac{a}{c} = \frac{P_{demanded}}{\left(1+\frac{a}{b}+\frac{a}{c}\right)} * \frac{a}{c} \tag{7.10}$$

$$p_{KHPP} = P_{PHPP}\frac{a}{b} = \frac{P_{demanded}}{\left(1+\frac{a}{b}+\frac{a}{c}\right)} * \frac{a}{b} \tag{7.11}$$

14. When cascade optimization controller determine task to implementation, it determine number of generators, which are necessary to start in each plant as:

$$\frac{P_{plant}}{P_{generator}} = n, \tag{7.12}$$

where P_{plant} - plant demanded power,

$P_{generator}$ - single generator power,

n - it can be fractional number, which should be round up to whole number.

15. After number of generators is determined Plavinas HPP each generators' optimal output power should be calculated. After Plavinas HPP optimization there are detected power difference between Plavinas HPP demanded and generated power.

$$\Delta P_{PHPP} = P_{optimal} - P_{PHPPafter(7.9)} \,, \tag{7.13}$$

where $P_{optimal}$ - as a result of optimization determined power,

$P_{PHPPafter(7.9)}$ - which calculated after (7.9) equation.

Acquiring difference, changes task for other plants' operating generators regarding Plavinas HPP ΔP value. The next step will be optimization of Kegums and Riga HPP operation mode.

$$P_{RHPPadjusted} = (P_{PHPPafter7.9)} + \Delta P_{PHPP})* \frac{a}{c} \quad (7.14)$$

$$P_{KHPPadjusted} = (P_{PHPPafter(7.9)} + \Delta P_{PHPP})* \frac{a}{b} \quad (7.15)$$

16. Optimal power distribution between plants ***third requirement***.

Fig.7.2. shows plants upstream and downstream levels: maximal allowable level, real level and minimal allowable level.

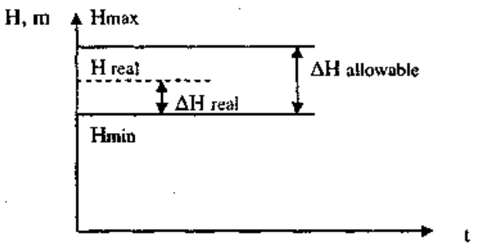

Fig. 7.2. Plants upstream and downstream levels.

Each plant has water reservoirs' upstream and downstream levels and allowable upstream and downstream levels change limits.

The third requirement, which should be taken into consideration, distributing load between plants is all plant worked water levels proportion equality (7.16).

$$\frac{\Delta H_{PHPP}}{\Delta H_{PHPPallowable}} = \frac{\Delta H_{KHPP}}{\Delta H_{KHPPallowable}} = \frac{\Delta H_{RHPP}}{\Delta H_{RHPPallowable}}, \quad (7.16)$$

where $\Delta H_{PHPP} = H_{PHPPreal} - H_{PHPPmin}$ (7.17)

$$\Delta H_{KHPP} = H_{KHPPreal} - K_{HPP\min} \quad (7.18)$$

$$\Delta H_{RHPP} = H_{RHPPteal} - H_{RHPP\min} \quad (7.19)$$

Values $\Delta H_{aloawable}$ for each plant set maintenance personal.

If plants related level dissatisfy condition (7.16), then it is necessary to adjust power distribution between plants, with aim, to satisfy equation (7,16). It can be reached by correcting plant's real water head *H*.

Let's see calculated water head $H_{calculated} = H_{plant} \pm \Delta H_{adjust}$, correction example.

Let us say, that equation (7.16) dissatisfies Riga HPP, it means:

$$\frac{\Delta H_{PHPP}}{1{,}5} \neq \frac{\Delta H_{RHPP}}{0{,}75} \qquad (7.20)$$

where 1,5; 0,75 are plants allowed water work-out $\Delta H_{PHPPallowable}$; $\Delta H_{RHPPallowable}$ meters per day values.

At first from (7.16) let's determine which should be $\Delta H_{RHPcalculated}$ value, to satisfy equation (7.16), it means:

$$\frac{\Delta H_{PHPP}}{1{,}5} = \frac{\Delta H_{RHPPcalculated}}{0{,}75} \qquad \Delta H_{RHPPcalculated} = 0{,}5\Delta H_{PHPP.}$$

Following upstream and downstream levels measurement results determine $\Delta H_{RHPPadjust}$
Determine adjustable value $\Delta H_{RHPPadjust}$

$$\Delta H_{RHPPadjust.} = \Delta H_{RHPPadjust} - \Delta H_{RHPPadjust^{\bullet}} = \Delta H_{RHPPreal} \pm 0{,}5\Delta H_{PHPP} \qquad (7.21)$$

In equation (7.4) instead of $\frac{P_{RHPP}}{H_{RHPP}}$ should be set expression $\frac{P_{RHPP}}{H_{RHPP} + \Delta H_{RHPPadjust}}$.

At positive water head correction result, to secure the equality (7.16) it is necessary to increase power P_{RHPP}, to speed up upstream level water workout. That mode should be maintained as long, as equation (7.4) will be satisfied.

In chapter proposed Daugava HPP cascade controller realizing operation algorithm is introduced and assumed ***requirements*** in it. Proposed algorithm realizes Daugava HPP cascade demanded generation power optimal distribution between plants, considering, that Plavinas HPP optimization is managed. Algorithm considers water reservoirs levels defined constraints for this power distribution.

To realize Daugava HPP cascade plants hydro units generators optimal control the following **automatic optimal control** system structural scheme is proposed, which operates after above described algorithm (see Fig. 7.3.).

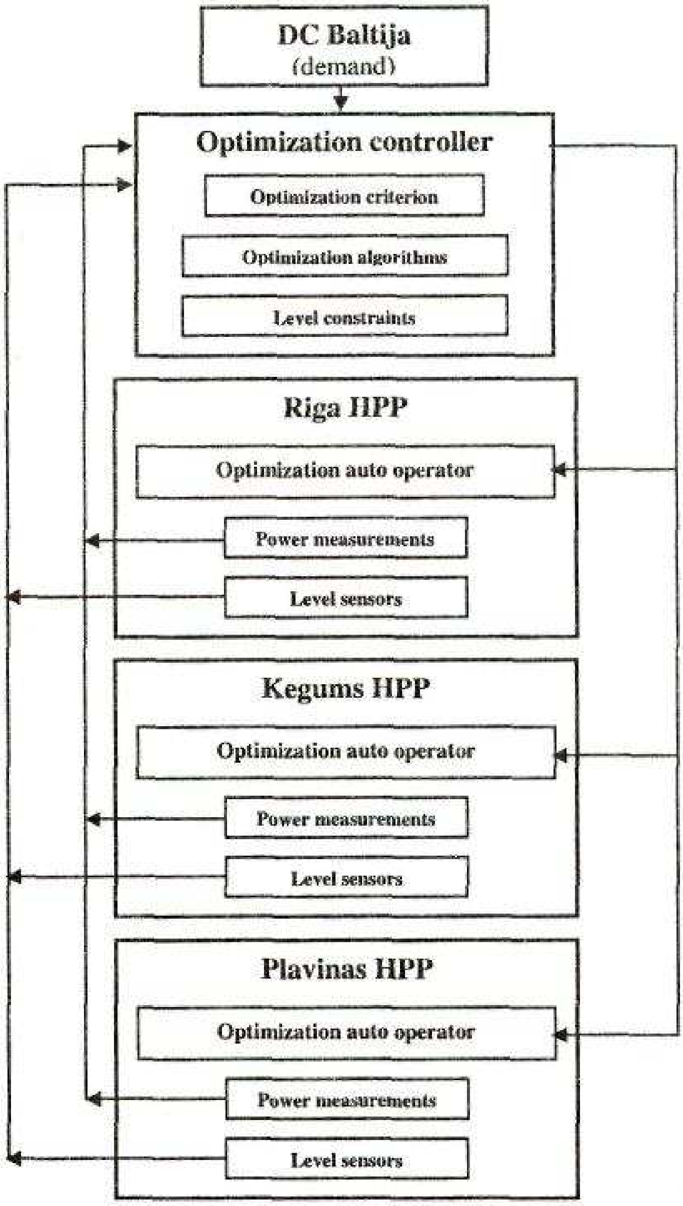

Fig. 7.3. Automatic optimal control system structural scheme

From each plant there should be provided data channels to optimization controller, to transfer plants each hydro units' power measurements and plant upstream and downstream level measurements.

The value of demanded power from dispatch center should not be changed. After power task receiving, optimizations controller considering optimization criterions, level constraints and using optimization algorithms, respectively gives new power orders (power settings) to each of the power plants, securing dispatch center demanded generation power settings are constant.

To manage Daugava HPP cascade plants hydro generators optimal control, following proposed methodology, existent control system should be supplemented with special optimization controller and should be improved or replaced existent plant auto operators to new, which manages to realize special optimization controller tasks.

8. THE DAUGAVA HPP CASCADE OPTIMAL CONTROL EFFICENCY ESTIMATION

Eighth chapter dedicated to the Daugava HPP cascade optimal control efficiency evaluation method example developing.

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER INVESTIGATIONS

Chapter includes main conclusions and recommendations for further investigations.

Investigation objectives and tasks are fulfilled, as results:

- Daugava HPP cascade hydro units control methods optimization was carried out during research. As the result there is proposed new hydro unit control method and new common hydro power plants control methodology.
- Semi-graphical method was developed and proposed to evaluate hydro units' operation efficiency. Method is based on turbine model characteristics modification and it's provides for optimization necessary characteristic family.
- As a result of modification, acquired families are easy to use in modern control devices.
- As a result of analyses, Plavinas hydro power plants unit operation optimization method was developed, which allows to determinate hydro units optimal operational mode, indirectly determinate real water head and water flow values.

- Hydro units' real water head determination method is developed and proposed, using which it is possible to optimize Plavinas HPP hydro units operation. Method is approved as a Latvia Republic patent.
- Developed methodology for Daugava HPP cascade hydro power plants operation modes optimization provides optimal power distribution between power plants.

Recommendations for further investigations:

- Using computer engineering and mathematical possibilities, it is possible to make proposed Daugava HPP hydro units operational modes optimization methodology description using one of the mathematical programming methods, hence developing mathematical model.
- Hydro units' governor dynamic investigation at further researches should be mandatory.
- Developed optimization algorithms should be taken into consideration at further units control system reconstruction or change.