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HYDRO GENERATION SCHEDULING FOR A ONE YEAR PERSPECTIVE

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ABSTRACT: Predominance of hydro power plant (HPP) generation in Electric power systems (EPS) needs coordinating among several HPPs in the river cascades. A technique for long-term generation scheduling is proposed for power systems with hydro power plants. A mathematical formulation of the problem supposes the application of dynamic programming method. An algorithm contains a number of simplifications to solve the problem in reasonable computing time. The results of yearly generation scheduling in the electric power system of Siberia show strong dependence of the total fuel cost on the optimal monthly electricity production by individual HPPs. The marginal prices of the electricity generated during a year and under different water conditions are calculated for power plants of the EPS of Siberia. The possibility of implementing the long-term optimal generation schedules at power plants by setting the electricity prices is shown.

KEY WORDS-- Hydrothermal power systems, Long-term generation scheduling, Dynamics programming, Electricity generation price, Optimal schedule implementation

I. INTRODUCTION

Long-term generation scheduling is a problem traditionally solved by the dispatching control of the interconnected power systems. It supposes consideration of the EPS operation through a year (scheduling period divided into the finite number of time intervals, usually months. The problem is particularly important for EPS with a large contribution of hydro power plants with long-term storage reservoirs into electricity generation.

Part of the initial information employed in solving the problem is uncertain and is represented by random values or processes. Particularly it concerns the forecast data on the water inflow to the HPP water reservoirs.

The objective of solving the problem is to reach maximum economic benefit from operation of the whole EPS during the scheduling period. Any of the values: the minimum level of the total electricity generation cost, the minimum average price of the electricity supplied to the market, the maximum total profit of suppliers and buyers can be considered as an objective function. More common is a least-cost scheduling carried out by a System Operator. Technical, ecological and economical constraints are to be satisfied for individual time intervals. Consideration is also given to the integral constraints for several intervals or for the whole year.

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Mathematically the long-term generation scheduling is a multi-time-interval stochastic programming problem with interdependence among the EPS operation variables at the time intervals.

The long-term generation scheduling fosters rational utilization of water resources, coordinated loading of generating equipment, enhancement of the system economic efficiency of the EPS operation. Therefore, the authors of many publications place a significant emphasis on development of the techniques for solving the generation scheduling problem [1-4]. Competitive behavior of generators in the electricity markets called for new approaches to hydrothermal system modeling, based on game theory implementation [5, 6]. Development of the dispatching control systems, introduction of new economic relations among water users and in the electric power industry itself call for improvement of the generation scheduling techniques. New capabilities of computers make it possible to specify the problem statement, apply the advanced computational methods and algorithms.

The variety of approaches arises due to different features of real hydrothermal systems. Many of them consider predominantly thermal systems, where the hydro-generation is marginal, and the main attention is paid to representation of thermal units. The paper presents the technique for long-term generation scheduling in large-scale power systems with predominant electricity production at HPPs. The proposed technique is developed on the basis of the dynamic programming procedure. The algorithmic innovations applied allow the considered problem to be solved on personal computers with moderate computational capabilities.

The need to coordinate the interests of the electric power industry subjects with the other water users requires new financial relations among them. Here it is important to economically evaluate water as a limited natural resource. The technique supposes calculation of prices of the water stored up in the reservoirs and drawn down through the HPP turbines. The algorithm of calculating the prices of electricity generated by HPPs is suggested. Consideration is given to the mechanisms of reaching the best system-wide economic benefit from EPS operation in an electricity market environment.

II. A TECHNIQUE FOR LONG-TERM GENERATION SCHEDULING

The technique implies the mathematical formulation of the problem; the choice of a numerical method for its solution; development of the algorithm, that makes the intensity; and computer implementation of the algorithm.

A. Mathematical statement of the problem

The minimum total variable (fuel) cost of electricity production at thermal power plants (TPP) for the considered scheduling period is assumed as a scheduling criterion. Following the optimality principle for the multi-time-interval processes, the objective function of the problem can be represented in the form:

$$min\ E[\sum_{i=1}^{I} c^t_{iTPP} * \widetilde{W}^t_{iTPP} + f^{\,t+1,T}(\widetilde{V}^{\,t+1,T})], t=1,\dots,T, \quad (1)$$

where: i is the TPP number, I is the total number of TPPs; c^t_{iTPP} is a price of electricity produced at the *i-th* TPP at interval t[1]; $\widetilde{W}^t_{iTPP}$ is a random amount of electricity produced at the *i-th* TPP at interval t; $f^{\,t+1,T}(\widetilde{V}^{\,t+1,T})$ is the function of the variable part of the cost for electricity generation at thermal power plants in the time, starting at interval $t+1$ to the end of the scheduling period; $\widetilde{V}^{\,t+1,T}$ is a vector of random water storages in the HPPs reservoirs at the beginning of the *(t+1)-th* interval (at the end of interval t); E is the symbol of expectation; T is the number of the considered intervals t in the scheduling period.

The function in the right side of (1) is a sum of current (for interval t) and future (to the end of the scheduling period) costs.

When searching for the minimum (1) the account is taken of the following constraints:

1) on turbine capacities

$$Q_j^{\,t} \le Q^t_{j\,max}, \quad j = 1 \dots J, \quad (2)$$

where Q^t_j is a water discharge through the turbines of the *j-th* HPP at interval t; $Q^t_{j\,max}$ is a maximum admissible discharge value for Q^t_j; J is the number of HPPs in EPS;

2) on water spill discharges:

$$S^t_j \le S^t_{j\,max}, \quad j = 1 \dots J, \quad (3)$$

where S^t_j is a spill discharge of excessive water at the *j-th* HPP at interval t; $S^t_{j\,max}$ is a maximum dam capacity at the *j-th* HPP with regard to the spill discharge of water at interval t;

3) on sanitary and water management regulations:

$$U^t_{j\,min} \le Q^t_j + S^t_j, \quad j = 1 \dots J, \quad (4)$$

where $U^t_{j\,min}$ is a minimum water discharge to the low head of the *j-th* HPP in accordance with the sanitary and water management regulations at interval t;

4) on water reserves in the HPP reservoirs:

$$V^t_{j\,min} \le \widetilde{V}^t_j \le V^t_{j\,max}, \quad j = 1 \dots J, \quad (5)$$

where $\widetilde{V}^t_j$ is random water storage in the reservoir of the *j-th* HPP at the beginning of interval t; $V^t_{j\,min}$, $V^t_{j\,max}$ are the minimum and maximum admissible values of water storage V^t_j;

5) on water balance:

$$\widetilde{V}^{t+1}_j = \widetilde{V}^t_j - Q^t_j - S^t_j + \widetilde{A}^t_j + (Q^t_m + S^t_m), \; j=1 \dots J \quad (6)$$

where $\widetilde{V}^{t+1}_j$ is random water storage in the reservoir of the *j-th* HPP at the end of interval t (at the beginning of interval $t+1$); $\widetilde{A}^t_j$ is a lateral water inflow to the reservoir of the *j-th* HPP at interval t; Q^t_m, S^t_m are a water discharge through turbines and a spill discharge from the upstream *m-th* HPP at interval t;

6) on electricity production at HPP W^t_{jHPP}:

$$W^t_{jHPP\,min}(t) \le \widetilde{W}^t_{jHPP} \le W^t_{jHPP\,max}, \; j = 1 \dots J, \quad (7)$$

where W^t_{jHPP} and $W^t_{jHPP\,max}$ are the minimum and the maximum electricity production at the *j-th* HPP at interval t; $\widetilde{W}^t_{jHPP}$ is a random amount of electricity produced at *j-th* HPP at interval t;

7) on electricity production at TPP:

$$W^t_{iTTP\,min} \le \widetilde{W}^t_{iTTP} \le W^t_{iTTP\,max}, \; i = 1 \dots I, \quad (8)$$

where $W^t_{iTTP\,min}$ and $W^t_{iTTP\,max}$ are the minimum and the maximum electricity production at the *j-th* TPP at interval t;

8) on power balance in the electric network nodes:

$$\widetilde{W}^t_{aTPP} + \widetilde{W}^t_{aHPP} - \sum_{b=1}^{M} \widetilde{W}^t_{ab} + \sum_{b=1}^{M} (1 - \Delta^{ab}) * \widetilde{W}^t_{ba} = W^t_{aD}, \quad b = 1, \dots M, \; a = 1, \dots N \quad (9)$$

where a is the number of a network node; N is the total number of nodes in the network; b is the number of the node connected to the node a; M is the total number of the nodes connected to the node a; $\widetilde{W}^t_{aTPP}(t)$ is random electricity production at thermal power plants connected to the node a at interval t; W^t_{aHPP} is random electricity production at hydro power plants connected to the node a at interval t; $\widetilde{W}^t_{ab}$ is a random power flow from node a to node b at interval t; W^t_{ba} is a random power flow from node b to node a at interval t; Δ^{ab} is power losses in the line ab (are expressed in shares of the power flow); W^t_{aD} is electricity consumption from the electric network in node a at interval t;

9) on electricity flows:

$$\widetilde{W}^t_{ab} \le W^t_{ab\,max}, \; b = 1, \dots M, \; a = 1, \dots, N, \quad (10)$$

[1] In formula (1) for simplicity consideration is given to the case where the electricity price c^t_{iTTP} is constant through the whole range of generation values W^t_{iTTP}. The suggested technique stipulates that the price c^t_{iTTP} should be set in the form of a step function of W^t_{iTTP}.

where $W^t_{ab\,max}$ is a maximum admissible electricity flow through the line *ab* at interval *t*. The variables of the problem are W^t_{iTPP} , W^t_{jHPP} , Q^t_j , S^t_j , V^t_j .

B. A Method for solving the problem

The method of dynamic programming has been applied to solve the problem. Owing to the method:

1. the general scheduling problem can be simplified by dividing it into several simpler optimization problems;
2. the water and electricity constraints can be considered at the end of each interval *t* within the year-long scheduling period;
3. it is possible to obtain not only the optimal values for the variables but the tool for a fast and simple recalculation of the optimal long-term generation in the event of changes in the external conditions during the scheduling period starting with any given interval *t*;
4. the price of the stored and discharged water can be calculated at time intervals of the scheduling period.

C. An algorithm of the problem solution

An algorithm has been developed to solve the problem (1)-(10). It contains a number of simplifications that reduce the total computational efforts and make solution of the problem achievable in the admissible time on the personal computers with moderate computation capabilities.

The first simplification consists in representation of the forecasted information on the lateral water inflows to the HPP reservoirs. Random information on the inflows for each time interval *t* is set by several inflow scenarios that correspond, for example, to low water inflow, normal water inflow and flood. Each scenario is considered with expected probability of its occurrence.

The second computational simplification is a preliminary construction of the functions of future cost (FFC) for each interval *t* [3, 7]. The FFC for interval *t* is calculated along with the analysis of system's optimal behavior in the future and calculation of costs at the intervals following interval *t*. For each interval *t* consideration is given to several initial values of water storages and different water inflow scenarios. The FFC for interval *t* is an expectation of the production cost and is represented in a piecewise-linear form [3]. It is used to consider the value of objective function (1) at the previous interval *(t-1)*.

The third simplification implies decomposition of the problem (1)-(10) into two subproblems. The possibility of decomposition follows from the fact that HPPs in the Russian EPSs have practically zero variable component of the production cost. This means that scheduling the EPS generation we consider the hydro power plants loading first and at maximum admissible amount (with account for constraints (2)-(7)). The electricity production at thermal power plants is actually scheduled at a known load of HPPs. Therefore solving the problem (1)-(10) we can sort out the following subproblems:

1. Determination of the optimal electricity production at HPPs disregarding thermal power plants and the network topology.
2. Calculation of the optimal generation at TPPs at known values of electricity production at HPPs with electricity flows consideration.

The first subproblem requires solution of a non-linear optimization problem. The second subproblem, at linearly set prices c^t_{iTPP} can be represented by the linear programming problem.

D. Software support

The software package MatLab v6.5 was used to implement the software support of the problem (1)-(10). The software package contains a set of standard optimization toolboxes for solving the problems of linear and non-linear programming, as well as embedded programming language. The embedded language and the set of toolboxes were employed to develop the computer program for solving the long-term optimal generation scheduling problem using the dynamic programming approach.

It took about 20 minutes to compute the optimal long-term operating conditions of the EPS of Siberia (the problem with 94 variables, 265 constraints, 12 time intervals) on the PC with processor AMD Duron 1100 MHz and 512 Mb operative memory. Here 90% of time was required for the back-substitution stage and 10% of time was spent on the forward elimination stage. The computation time is quite long which is due to the specific feature of the MatLab package, namely due to the fact that the optimization toolboxes, as well as the program itself are the initial files and should be converted to the machine-language code. The computation time can be essentially reduced by preliminarily converting these functions and the program to the binary form (machine-language code).

III. DETERMINATION OF PRICE OF WATER AND ELECTRICITY PRODUCED BY HPPs

Solving the problem (1)-(10) along with the optimal values of the variables, the marginal prices of water and electricity produced by each HPP are determined.

When solving the long-term generation scheduling problem two types of water prices are determined: the price of water stored in reservoir of every HPP and the price of water discharged through the HPP turbines.

The price of water stored in the reservoir of the *j*-th HPP is calculated as a dual variable (Lagrange multiplier) of problem (1)-(10) that corresponds to the *j*-th water balance equation (6). The price of discharged water for the single or downstream HPP in cascade equals the price of stored water. For the upstream HPP in cascade the price of discharged water is equal to a linear combination of prices of discharged water of the considered HPP and the downstream plants [3].

To solve problem (1)-(10) the marginal price of electricity produced by the *j-th* HPP is determined for each time interval of the considered scheduling period:

$$c^{t}_{jHPP} = C^{t}_{jp} \cdot Q^{t}_{j} / W^{t}_{jHPP}, \quad j = 1 \dots J \qquad (11)$$

where c^{t}_{jHPP} is the price of electricity generated by the *j*-th HPP in time interval *t*; C^{t}_{jp} is the price of water discharged through turbines of the *j*-th HPP in interval *t*.

The prices of electricity produced at HPPs take into account:

- specific features of water limitations of each HPP;
- uncertainty of water inflow to HPP reservoirs;
- location of HPPs in cascade;
- electricity generation at other power plants of EPS;
- network constraints in EPS.

It is worth noting that the electricity price (11) does not reflect the cost price of electricity at the *j*-th HPP, but is equal to the saved total fuel cost with small increase of HPP production. The price calculated by expression (11) is the marginal nodal price of electricity at HPP for a long time from the interval *t* to the end of scheduling period in terms of water, energy and network constraints.

IV. NUMERICAL ANALISIS OF LONG-TERM OPTIMAL OPERATING CONDITIONS IN EPS OF SIBERIA

The calculation-based studies were aimed to test the suggested technique and to analyze the factors influencing the optimal load of power plants and the electricity prices in EPS of Siberia.

The calculations were performed on the 30-bus sample system (Fig. 1) with 38 branches, 8 thermal power plants, and 5 hydro power plants. All HPPs have large reservoirs with the year or two-year water accumulation. HPPs in buses 23, 24 and 26 are operated in one river cascade. HPPs 15 and 17 are located in the other river cascade. Regional power utilities were considered to be electricity consumers. The optimization problem for long-term scheduling numbered 94 variables and 265 constraints.

The calculations were performed for one calendar year consisting of 12 monthly intervals, in our case for the year of 2001 that was a high-water year.

The amounts of thermal and hydro generation, water discharges through turbines, spill discharges, water storage in reservoirs and fuel costs of electricity production at thermal power plants were obtained for each month of the year. The calculations have proved the effectiveness of the technique.

The profile of electricity and heat demand as well as natural conditions in Siberia predetermine an uneven loading of thermal and hydro power plants over an annual scheduling cycle.

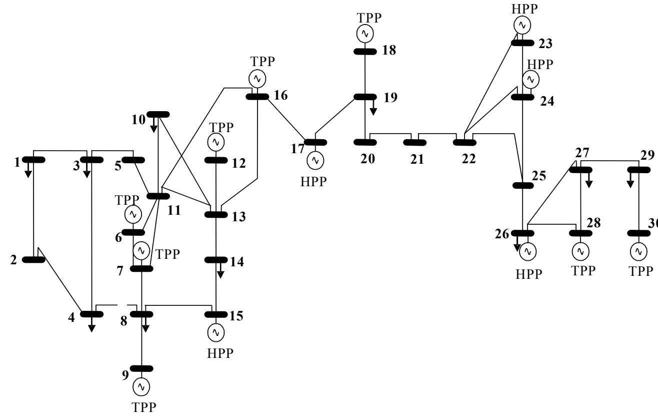

Fig.1. Sample system configuration

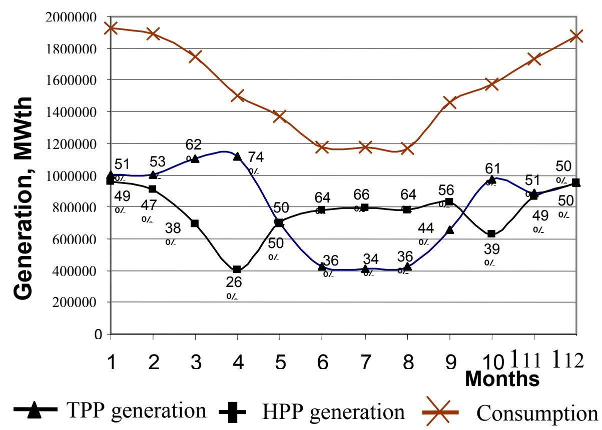

Fig. 2. Total consumption and production of electricity by thermal and hydro power plants in EPS of Siberia

Fig. 2 illustrates the unevenness of the optimal thermal and hydro generation at the actual water level of 2001. At the summer period (intervals 6-8) hydro generation reaches 66%, which is caused by the spring-summer flood, schedules of reservoir filling and requirements of other water users. And due to high water in 2001 and seasonal decrease in electricity consumption the water spill discharge amounted to 7.31 km^3 in summer and autumn intervals. At the pre-flood intervals (months 2-4), when HPPs draw down reservoirs to the minimum levels, electricity generation sharply falls and their share in the total production decreases to 26%.

Deviation in hydro generation from the optimal plan has a pronounced effect on economic indices of EPS operation. For example, the uncoordinated growth of electricity production at the HPP in bus 24 only in September 2001 by 14.3% (from the optimal volume of 2623490 to 3000000 MWh) could lead to additional water spill discharges of 1.22 km^3, decline of the total annual hydro generation by 3%, which in turn increases the total fuel cost in EPS by about 1%.

In the electric power system with a considerable share of hydro generation, the nature of inflow to the reservoirs

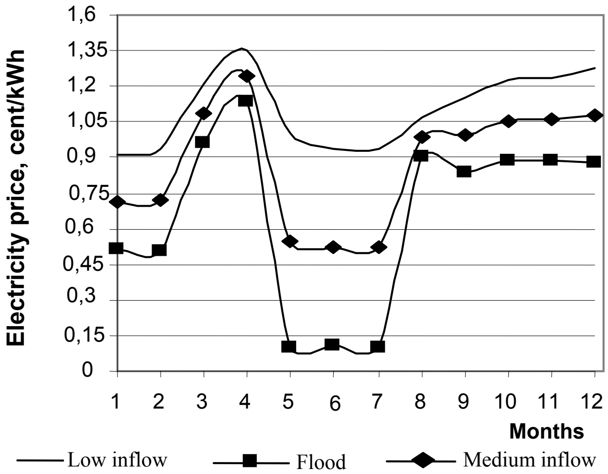

Fig. 3. Electricity price at the HPP in bus 26 (including capacity price)

determines both the output of power plants and the level of prices of electricity generated.

For HPPs in EPS of Siberia the marginal electricity prices are calculated for different months of a year and for different conditions of water inflow. The curves in Fig. 3 show that for the HPP in bus 26 the price level varies significantly during a year and depends on the water inflow to the river basin. The situation for the other Siberian HPPs is similar. The higher the inflow and the larger the volumes of water stored for electricity generation, the lower the produced electricity price. The prices at some HPPs from May to July in low-water inflow can be 6 times higher than the prices established at the flood inflow. In summer with medium water inflow the prices are 1.5-2.5 times lower than the prices corresponding to the autumn season.

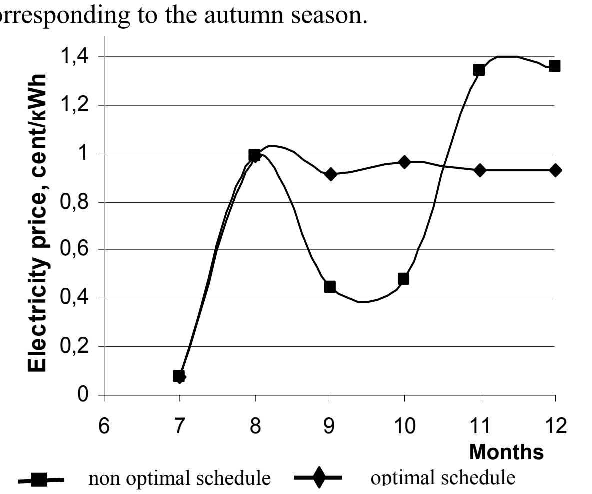

Fig. 4. Electricity price at the HPP in bus 24 (including capacity price)

Any deviation of hydro generation from the optimal schedule leads to rise in electricity prices. Thus, the hypothetical increase in electricity production by the HPP in bus 24 in September 2001 by 14.3% from the optimal amount brings significant change in electricity price at this plant (Fig. 4). At the optimal schedule the price curves are flatter. Increase in electricity generation at interval 9 leads first to a noticeable price fall due to replacement of more expensive thermal generation. In subsequent months the electricity price at this HPP rises because of decreasing efficiency of electricity production with the plant operation at lower heads and additional water spill discharges at the other plants.

V. IMPLEMENTATION OF ELECTRICITY GENERATION PLANS IN AN ELECTRICITY MARKET ENVIRONMENT

Since HPPs belong to different owners (shareholders) the interests of power plants and water users do not often coincide. The actual hydro generation, therefore, does not provide often a really optimal loading of generation capacities.

The spot market, whose principles will underlie the wholesale market in Russia, is also little adapted to optimal generation scheduling for a long time interval. The hourly clearing prices of electricity serve as key signals in such a market. And hence, the mechanism of this market can ensure reliable and optimal EPS operation only for a short-term interval. The highest system effect owing to hydrothermal generation can be achieved, if the centralized long-term generation scheduling in EPS is preserved. This is envisaged in the list of problems for the system operator on planning and control of EPS operation conditions.

At the same time the long-term optimal plans of electricity production that are developed by the system operator become optional for implementation by market participants. Independent generation companies often follow their commercial interests, and at some intervals can deviate from the optimal schedule for electricity generation. Then it becomes important to encourage the market participants to follow the long-term optimal generation schedule from the standpoint of the whole system.

The desirable system effect in EPS may be achieved not by the obligatory dispatcher command, but by setting the optimal price values for individual suppliers. In the wholesale electricity markets these prices can be applied as economic signals capable of providing the optimal or near-to-optimal generation in hydrothermal systems.

For the conditions of perfect competition when the bid of any producer has negligible effect on system marginal price the best strategy is to bid electricity to the market at the true production cost [8]. Such kind of bids leads to the marginal price, which provides the producers with the maximum profits [8]. The same conclusion is valid for nodal marginal prices as well. If the optimal generating schedule is developed by the System Operator using the true production cost and optimal nodal marginal prices are obtained the producers are encouraged to generate the amounts of electricity that correspond to the optimal generating schedule. Deviation from these amounts will reduce the producers' profits.

According to the wholesale market rules in Russia large HPPs do not submit the prices in their bids. Therefore large HPPs do not effect the market prices. Following the nodal marginal prices obtained from the long-term generation schedule a producer can calculate the amount of generation providing the maximum of its profit. Certainly, power plants should be informed on the nodal prices in advance.

When nodal marginal prices c^t_{iTPP} and c^t_{jHPP} are known, electricity producers can obtain the amounts of generation W^t_{iTPP} and W^t_{jHPP} from solving the problem:

$$min\ [\sum_{i=1}^{I} c^t_{iTPP} W^t_{iTPP} + \sum_{i=1}^{I} c^t_{jHPP} W^t_{jHPP}\ ], \quad t = 1,...,T$$

subject to constraints (2)-(10).

For the optimal generation loading in terms of prices it is important to know how accurate the setting of prices should be. The distorted setting of prices leads to non-optimal generation at power plants and hence, to decrease in the economic efficiency of system operation. A numerical study has shown that a 10% inaccuracy in setting the electricity price at large HPPs can result in a 1% excess of fuel cost in EPS of Siberia. The larger is the installed capacity of power plant, the more accurate should be the fixed price of its produced electricity.

VI. CONCLUSION

1. The non-coordinated behavior of some HPPs concerning electricity generation in a spot market environment causes a decrease in economic efficiency of EPS operation and irrational use of water resources. The best system effects can be achieved, if the long-term centralized scheduling of hydrothermal system operation is preserved.
2. The technique for long-term optimal generation scheduling that is based on the multi-time-interval (dynamic) consideration of electricity generation for a scheduling period is described. It comprises a mathematical formulation of the problem, choice of the dynamic programming method as a computational procedure and development of the algorithm to solve the problem in a reasonable computing time. The technique is used to calculate prices of the stored and discharged water as well as the price of electricity produced by each HPP in the optimal system operation conditions.
3. Numerical studies on the efficiency of generation scheduling for EPS of Siberia have revealed strong dependence of the annual economic indices on observance of the optimal electricity production amount by each HPP in every month of the studied year. A 14.3% increase in electricity production at one HPP in September 2001 above the optimal value could lead to: additional spills of excess water at the other power plants, a 3% decrease in the total annual hydro generation and increase in the total fuel costs in EPS.
4. The electricity prices at HPPs vary considerably over a year. They depend on both stored water and lateral inflow to reservoirs. The larger the water resources of HPP, the lower the price of electricity generated. Deviation of the HPP operation from the optimal production volume increases the electricity price level at this HPP and at other power plants.
5. The long-term optimal operation conditions of hydrothermal system can be realized by setting the electricity price for the wholesale market participants. When the prices of hydro generation are set inaccurately, the benefit of optimization will be lower and the costs of thermal generation will be higher. The larger is the installed capacity of HPP, the more accurately should be set the price of electricity produced by it.

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