Optimal control of Electric Power system with cogeneration and Hydro Power Plants of over-year storage in the Eastern Regions of the RF

A.M.Kler, Z.R.Korneyeva, P.Yu.Elsukov

The structure of electric power systems (EPSs) in the eastern regions of the RF is characterized by a sizable share of cogeneration plants (CPs) and hydro power plants (HPPs) of the over-year storage. An optimization technique of long-term operating conditions of EPSs has been devised to optimally control their current development and operation by using a tree of combinations of inflow conditions. A method for coordination of optimization problems of power system operation with different duration of the considered periods and a method for graphic construction of energy characteristics of cogeneration plants that are applicable to optimization of power system operation are suggested. Application of the technique is illustrated by the example of the bulk EPS in the eastern region of Russia that includes a cascade of three HPPs and eight CPs.

Keywords**: optimization of operation; EPS; CP; HPP; long-term operating conditions; over-year storage reservoirs; randomness of inflow conditions; fuel costs.**

1. INTRODUCTION

The methods of stochastic dynamic programming [1-3] and stochastic dual dynamic programming [4] are most widely used to optimize long-term operating conditions of EPSs with cogeneration and hydro power plants with over-year storage reservoirs. Both groups of methods are based on the multi-step (multi-stage) process. The whole considered period (of several years long) is divided into some number of time intervals (e.g. with an interval duration of one month). The function of conditionally optimal costs for the power system that depend on water reserves in HPP reservoirs at the beginning of this interval is generated for each interval. An approach based on reduction of these optimization problems to the problems of linear or nonlinear mathematical programming is also applied to optimization problems of long-term EPS operating conditions in addition to the methods of stochastic dynamic and stochastic dual dynamic programming [5-7]. The currently applied methods of nonlinear programming can solve problems with thousands of optimized parameters and constraints [5]. It should be noted that dimension of the problems solved by these methods is in this case lower than that of the problems solved by the method of stochastic dual dynamic programming, but the solution process is simpler. In all the considered methods capacities of power plants are determined based on the assumption that at the end of the time interval water reserves at different lateral water inflows, but equal water reserves at the beginning of the interval should be the same. It makes it possible to construct a single optimal trajectory of water reserve variation over the whole considered period, which considerably simplifies an optimization process. However, the requirements of the single optimal trajectory decreases efficiency of the solutions obtained. It should be underlined that as the current time instant approaches some time interval, uncertainty of water inflow at the given time interval decreases. If a certain combination of inflow conditions is considered at the specified interval, the control actions optimal for this combination should be taken. Hence, we have a tree of optimal trajectories rather than one.

As a result of constructing the indicated tree of optimal trajectories an approach based on the use of a tree of combinations of EPS operation conditions [8] and the solution of nonlinear mathematical programming problems is developed. It was intended, however, for power systems with HPPs having seasonal storage reservoirs. For such systems the considered period is taken equal to one year with its start at the flood beginning. Therefore, water reserves in HPP reservoirs at the beginning and end of the period are known and equal to their minimum values.

A.M.Kler, Z.R.Korneyeva, P.Yu.Elsukov are with Melentiev Energy Systems Institute of SB RAS, Irkutsk, Russia.

An essential flaw of the optimization method of EPS operation is its two- step character [8]. At the first step the EPS operation is optimized independently at individual time intervals (for the reference operating conditions) at different energy cost ratios between HPPs and CPs. At the second step a coordinated optimization of EPS operation is performed for the whole considered period. In this case EPS performances at individual time intervals are determined as convex linear combinations of the corresponding characteristics of reference operating conditions. The decomposition coefficients of the current operating conditions are the optimized parameters for the second step. Therefore, any change in inflow conditions calls for cumbersome calculations of reference operating conditions to be repeated. At present owing to sharp increase in the performance of computer engineering it became possible to optimize long-term operating conditions of EPS at one step.

The work aims to modify the method in [8] for the single-step optimization of EPSs with CPs and HPPs with over-year storage reservoirs. The problem topicality is explained by the fact that in Russia's power systems with HPPs of over-year storage (Irkutskskaya, Norilsko-Taimyrskaya, etc.) the share of CPs is large.

When optimizing long-term operating conditions of EPS including HPPs with over-year storage reservoirs, the considered period should cover several years. In this case account is to be taken of a random character of water inflow into the HPP reservoirs. If HPPs form a cascade, the "external" water inflow to the cascade is considered. A random character of water inflow can conveniently be taken into consideration by using a tree (graph) of combinations of EPS operation conditions over the considered period [8]. The whole period of EPS operation is divided into time intervals, the number of tree branches at some interval being larger or at least no less than at the previous interval. It makes it possible to consider expansion of the range of change in the random values, as the time interval moves away from the beginning of the considered period.

Specified values of water reserves in HPP reservoirs (that are characterized by water levels in the reservoirs and heads at HPP dams) correspond to each tree vertex. Specified values of water inflows into the reservoirs and conditional probability of this combination of inflows correspond to each branch. The conditional probability of a branch is determined under assumption that the EPS operation process runs through the initial node of this branch. The sum of conditional probabilities of all tree branches emerging from one vertex is equal to unity. The probability of the tree vertex is equal to the probability of its branch. The probability of the tree branch is equal to its conditional probability multiplied by the probability of the initial branch vertex. Since the water reserves in HPP reservoirs at the beginning of the considered period are assumed to be known, the probability of the initial tree vertex equals unity. Since the probability of the initial tree vertex and the conditional probabilities of its branches are known, it is possible to determine probabilities of all its vertices and branches. If we assume, for example, that three branches corresponding to low-, average- and high-water inflows run from each node, such a full tree will be of the form shown in Fig. 1.

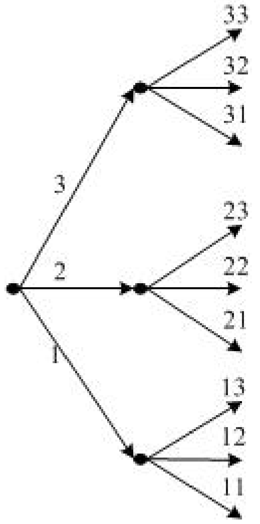


Fig. 1. A tree of combinations of inflow conditions. 1 – indicator of low-water time interval; 2 – indicator of average-water time interval; 3 – indicator of high-water time interval. Designation of the tree branch is formed as designation of the previous branch + indicator of the interval inflow, to which the branch belongs.

EPS performances at combinations of inflow conditions that correspond to a certain tree branch are determined by calculation of one or several representative operating conditions. These performances in turn depend on optimized parameters in the representative conditions (capacities of CPs and HPPs, idle discharges at HPPs). And the optimized parameters must be chosen so that the technological constraints on the ranges of change in capacities of CPs and HPPs, transfer capabilities of overhead transmission lines, ranges of change in water levels in HPP reservoirs and water flow rates at the HPP dam sites, etc. should not be violated.

2. PROBLEM STATEMENT

Find the optimized parameters in the representative operating conditions of EPS that are determined by the tree of combinations of water inflows such that the mathematical expectation of discounted fuel costs for the considered period is minimal. In so doing the indicated technological constraints should be met in each operating condition. Water reserves in HPP reservoirs at the beginning of the considered period are specified. This problem will be called problem I.

In the work this problem is reduced to the nonlinear mathematical programming problem. The considered period of problem I is divided into time intervals equal as a rule to one year. It is suggested that the values of water reserves at the end of the period of problem I should be determined by solving an auxiliary problem II because of the following reasons.

- The considered period start of problem II coincides with the time of the considered period end of problem I and the length of the considered period and the time intervals of problem II are taken as a rule the same as in problem I.
- Beyond the considered period of problem I the values of electric loads and generation capacities are forecasted by year of the considered period of problem II. If there is no information concerning change in electric loads and unit commitment, it is reasonable to consider the system work with fixed loads and constant unit commitment that correspond to loads and unit commitment at the end of the considered period of problem I.
- Water reserves at the considered period start of problem II are equal to expectations of these reserves at the considered period end (stability condition).

Water reserves at the considered period start of problem II, to which the minimum expectation of fuel costs for the considered period of problem II corresponds, provided the stability condition is satisfied, are called optimal reserves. When solving problem I the initial water reserves are set and the expectations of water reserves at the considered period end are assumed to be equal to their optimal values obtained by solving problem II.

Mathematically problem I is formulated as follows. Find

$$\min_{x_{ji}^{opt}} \sum_{t=1}^{T} d_t \left\{ \sum_{\forall j \in Q_t} \left[V_j \left(\sum_{i=1}^{n} u_{ji} \right) \right] \right\}, \quad (1)$$

subject to

$$G_{ji}\left(x_{ji}^{opt}, W_{ji}^{in}, S_{ji}\right) \geq 0, \quad (2)$$

$$W' \leq W_{ji}^{out} = \varphi\left(x_{ji}^{opt}, W_{ji}^{in}, S_{ji}\right) \leq W'', \quad (3)$$

$$u_{ji} = \phi\left(x_{ji}^{opt}, W_{ji}^{in}, S_{ji}\right), \quad (4)$$

$$W_{jk+1}^{in} = W_k^{out}, \quad (5)$$

$$W_{q_1}^{in} = W_{jn}^{out}, \forall q \in \psi_j, \quad (6)$$

$$W_{h_1}^{in} = W^o, \forall h \in \psi_1, \quad (7)$$

$$V_q = V_j P_q, \forall q \in \psi_j, \quad (8)$$

$$\sum_{\forall l \in Q_T} V_l W_{ln}^{out} = \widetilde{W}_T, \quad (9)$$

$$x'^{opt}_{ji} \leq x_{ji}^{opt} \leq x''^{opt}_{ji}, \quad (10)$$

$$i = 1,\ldots,n;\ j = 1,\ldots,D;\ k = 1,\ldots n-1;$$

where d_t - a discount index for the t–th time interval; V_j - a probability of inflow conditions corresponding to the j–th tree branch of conditions; n - the number of representative operating conditions considered at one time interval; u_{ji} - fuel costs of power system in the i–th representative operating condition at the combination of inflow conditions corresponding to the j–th tree branch; T - the number of intervals in the considered period; Q_t - a set of numbers of tree branches of inflow conditions that refer to the *t*–th interval of the considered period; G_{ji} - a vector of inequality constraints in the *i*–th representative operating condition corresponding to the *j*–th tree branch of inflow conditions; x_{ji}^{opt} - a vector of optimized parameters in the *i*–th representative operating condition corresponding to the *j*–th tree branch; W_{ji}^{in} - a vector of water reserves in HPP reservoirs at the beginning of the *i*–th representative condition corresponding to the *j*–th tree branch of conditions; W_{ji}^{out} - same at the end of the *i*–th operating condition; S_{ji} - a vector of initial data specifying inflow conditions in the *i*–th representative operating condition corresponding to the *j*–th tree branch of inflow conditions; ψ_j - a set of numbers of branches emerging from the same tree vertex, to which the *j*–th branch belongs; D - the number of branches in the tree of inflow conditions; W^O – a vector of water reserves in HPP reservoirs at the considered period start; p_q - a conditional probability of inflow conditions corresponding to the *q*–th branch; W', W'' - vectors of minimum and maximum admissible values of water reserves in HPP reservoirs; x'^{opt}_{ji}, x''^{opt}_{ji} - same for optimized parameters; $\widetilde{W}_T$ - a vector of required values of expectations of water reserves in HPP reservoirs at the considered period end (is determined at solution of problem II).

Mathematical formulation of problem II differs from the above formulation of problem I in the following way: a set of optimized parameters of problem II includes optimized operation parameters x_{ji}^{opt} along with water reserves at the beginning of the considered period W^o; additional conditions are also taken into account:

$$\widetilde{W}_T = W^o \quad , \qquad (11)$$

$$W' \le W^o \le W'' \qquad (12)$$

In expression (1) index t varies from $T+1$ to $T+T_{II}$, where T_{II} – the number of intervals in the considered period of problem II.

If the considered period of problem I or II is long the number of branches in the "full" tree will be quite large. Therefore, the need arises to reduce the number of nodes and branches in the tree of combinations. The reduction can be made by integrating the variants of water inflow into cascade in the considered period, that have close energy-economic equivalent. For calculating the equivalent it is necessary to take into account the economic value of one and the same amount of water inflowing into one and the same water reservoir in different years of the considered period. This is related to discounting of costs. Thus, the energy-economic equivalent is determined as follows (with an interval equal to 1 year):

$$D^j = \sum_{t=1}^{T} d_t \cdot \sum_{l=1}^{K} G^j{}_{tl} \cdot S_l \;, j = 1,..,M, \qquad (13)$$

where T – the number of years in the considered period; K – the number of HPPs in a cascade; M – the number of branches in the full tree in the T–th year (the last year of the considered period); $d_t = \frac{1}{(1+\alpha)} \cdot (t-1)$ - a discount index; α – a discount factor; $G^j{}_{tl}$ - «external» inflow in the *t*–th year into the *l*–th reservoir, that refers to the "full" tree branch that relates the tree's root vertex to the *j*–th exit vertex; S_l - energy value of water coming to the reservoir of the *l*–th HPP (is equal to the amount of electricity generated by the *l*–th HPP and by cascade HPPs located below, using the volume of water inflowing into the *l*–th HPP reservoir; and is determined at rated water heads at HPP dams).

All *M* variants of inflow are grouped into a specified number of groups *N*, according to the value of index D^j. One "average" variant is selected for each group. This variant is assigned the total probability of realization of all variants in a group. The branches and nodes of such variants make up a "reduced" tree of combinations of inflow conditions. For the reduced tree the optimization calculations are carried out. The algorithm of constructing the “reduced” tree is arranged so that for all N variants of its inflow the probability is specified. The variant with the least inflow should be assigned the probability on the basis of the water inflow required to enable power system to ensure electricity supply to consumers without limitations.

For optimization of EPS operation several representative operating conditions are considered. The heat loads of cogeneration plants in each variant may be assumed to be known. In this case to model CP it is necessary to know the range of change in its useful electric power at specified heat loads, and relationship between CP fuel consumption and its useful electric power in this range. The relationship is called energy characteristic of CP. In the work energy characteristics of CP are represented by two linear sections, one of which shows operation of cogeneration turbines with condensers according to cogeneration condition and the other - according to the condensing one. Mathematical model of HPP [8] used in the work takes into consideration linear dependence of specific water consumption for electricity production on water heads. In the mathematical model of transmission line [8] the squared relationship between active power losses and the value of transmitted active power is assumed.

The mathematical models of HPPs, CPs and transmission lines are used to construct the mathematical model for calculation of representative operating conditions of electric power system. The model includes the “water“ connection among HPP reservoirs if they belong to one cascade, and a scheme of transmission lines in the power system. In the model active powers of consumers and operating parameters to be optimized (active powers of power plants, idle discharges at HPPs, etc.) are specified. As a result the total cost of fuel consumed at CP in some period of time during which the calculated representative operating condition lasts, as well as water reserves (heads) in HPP reservoirs at the end of this period are determined.

The Computer-Aided Program Generation software is applied to construct a mathematical model for calculating representative operating conditions of EPS. Based on the analysis of graphical scheme of a studied object and mathematical models of its individual components the software enables automatic generation of a program for calculation of this object in the FORTRAN language [9].This software can also be used to construct the model for calculation of the entire set of representative operating conditions specified by the tree of combinations of inflow conditions and to solve the nonlinear mathematical programming problems I-II.

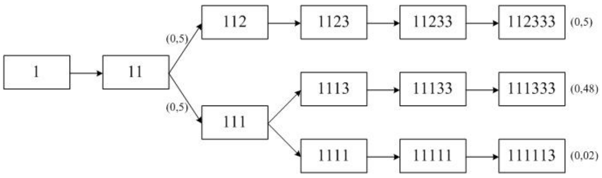
3. AN EXAMPLE OF POWER SYSTEM OPERATION OPTIMIZATION

Optimization of long-term operating conditions of a power system that includes a cascade of hydropower plants and coal-fired cogeneration plants is considered as an example. The power system includes three HPPs, two of which with over-year storage reservoirs (HPP-1 and HPP-2) and eight cogeneration plants with a total installed capacity of 3520 MW. Table 1 presents characteristics of HPPs in the power system.

TABLE 1. CHARACTERISTICS OF HPPS IN THE POWER SYSTEM

Characteristic	HPP-1	HPP-2	HPP-3
Installed capacity, MW	662	4500	3840
Long-term average electricity output, billion kWh	4.1	22.5	21.9
Maximum/ minimum head, м	29.8/28.4	105/95	87.5/86
Usable storage, km^3	46.4	48.2	2.77
Reservoir area, km^2	33000	5470	1873
Long-term average inflow into the reservoir, km^3/year	60.5	91.7	99.7

The considered period of problem I was assumed equal to 6 years, and the intervals into which the period was divided were equal to 1 year. The same assumptions were made for problem II. The reduced calculation tree of power system inflow conditions is given in Fig.2.



Fg.2. Reduced calculation tree of power system inflow conditions.

Fig.2 has the same principle of notations for the tree branches as Fig.1. Figures in brackets show the inflow probabilities in corresponding branches. For simpler illustration of the calculation results only three exit vertices are assumed in the reduced tree.

The calculations were made for two typical operating conditions: average winter (5760 hours long) and average summer (3000 hours long) conditions. In the average winter conditions CPs have average heat supply during heating period and in the average summer conditions – during non-heating period. Electric loads in the average winter and average summer conditions in the first year of the considered period are specified. In the next years the load at power system nodes is assumed to increase by 2%. Electric loads by year of the considered period of problem II were taken identical and equal to loads of the last year of the considered period of problem I. The CP fuel prices for different power plants were assumed varying in the range from 800 to 900 rub/tce. To determine electricity output the availability factor of CP generation equipment was assumed equal to 0.9 in the heating period and to 0.75 – in the non-heating one. For HPPs the availability factor was taken equal to 0.9 during the whole year. Optimal values of mathematical expectation of water heads on dams of HPP-1 and HPP-2 at the end of the considered period of problem I were obtained from solving problem II. For HPP-1 the mathematical expectation was 29.1 m and for HPP-2 – 102.5 m. As an example (Table 2) the main operating parameters of HPPs and CPs in power system are presented over the considered period for average winter and average summer operating conditions obtained by solving problem I.

TABLE 2. MAIN INDICES OF HPP AND CP OPERATION OVER THE CONSIDERED PERIOD (IN NUMERATOR - INDICES OF AVERAGE WINTER CONDITION, IN DENOMINATOR – INDICES OF AVERAGE SUMMER CONDITION)

Number of year	Number of branch	HPP capacity, MW	CP capacity CP, MW	Fuel costs, million rubles
1	1	5316/5574	3029/2426	8.79/4.33
2	11	5466/4637	3036/2422	8.14/4.01
3	112	6767/5919	1966/1324	7.14/3.61
3	111	5586/4736	3076/2454	7.56/3.72
4	1123	6976/5977	1922/1392	6.60/3.34
5	11233	6903/6704	2141/1861	6.17/3.13
6	112333	5795/5856	3340/1772	6.09/2.89
4	1113	7096/6092	1810/1280	6.57/3.34
4	1111	5719/4833	3093/2489	7.01/3.45
5	11133	6930/6718	2118/1848	6.17/3.13
6	111333	5797/5864	3340/1765	6.10/2.89
5	11111	5826/5956	3154/2571	6.51/3.20
6	111113	5800/5066	3340/2543	6.10/2.96

Findings presented in Table 2 allow one to forecast power and capacity balances, and determine power reserves in EPS and required volumes of fuel supply to CPs in the power system over the considered period, depending on HPP reservoir inflow.

4. CONCLUSION

A technique for optimization of long-term power system operation has been developed on the basis of a tree of optimal trajectories of water levels in HPP reservoirs. Application of the technique is exemplified by the power system including a cascade of three HPPs and eight CPs.

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6.BIOGRAPHIES

Alexander M.Kler – Head of Department of Thermal Power Systems at Melentiev Energy Systems Institute, SB of RAS, Irkutsk, Russia, Doctor of Technical Sciences, Professor. Main research interests are: comprehensive studies of thermal power systems (thermal energy, energy and chemical engineering plants, thermal power plants); studies of perspective energy and chemical engineering plants on fossil fuel, optimization of thermal power plant and electric power system operation.

Zaituna R. Korneyeva – Senior researcher at Melentiev Energy Systems Institute, SB of RAS, Irkutsk, Russia, Candidate of technical sciences, Associate professor. Main research interests are: mathematical modeling and optimization of cogeneration plant and electric power system operation.

Pavel Yu. Elsukov – Junior researcher at Melentiev Energy Systems Institute, SB of RAS, Irkutsk, Russia. Main research interests are : mathematical modeling and optimization of cogeneration plant and electric power system operation.