Search for a compromise between the interests of water users while forming the operating modes of HPP cascade

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Abstract. At present, there is no effective model of using a cascade of hydroelectric power stations in Russia, which allows equally to take into account the interests of all water users (consumers of agricultural products, fisheries, river transport, hydropower, water supply of the population and industry, etc.). The article provides a description of the developed methodology and software for optimizing the operating modes of a hydroelectric power station cascade using the example of the Volga-Kama cascade of Russia. The developed technique has proved itself as an effective means of finding compromise solutions in the formation of the regimes of operation of the hydroelectric power station cascade.

1. Introduction

Hydropower is one of the main industries in the power industry of Russia. The total installed capacity of hydropower plants in Russia is 48.5 GW or 20% of the total installed capacity of the unified energy system of Russia. In 2018 HPPs generated 178.3 million kWh of electricity, or 17% of the total electricity production in the country.

Possessing high regulatory capabilities, hydropower plants perform the following functions in the energy system of Russia: electricity generation; operational reserve; frequency control of electric current and coverage of the variable part of load schedules; voltage regulation by generating reactive power in a synchronous compensator mode (1).

The use of the hydropower potential of large rivers with the help of one hydroelectric station is most often impractical for environmental, technical and economic reasons. On the major rivers of Russia, the most characteristic is the construction of large cascades of hydroelectric power plants, with large reservoirs providing the most rational use of water resources (2-7).

The largest cascade of hydropower plants in Russia is represented on the rivers:
- Angara river (Irkutsk HPP - 662.4 MW; Bratsk HPP - 4515 MW; Ust-Ilim HPP - 3840 MW, Boguchanskaya HPP - 2997 MW);
- Yenisei river (Sayano-Shushenskaya HPP - 6400 MW; Mainskaya HPP - 321 MW; Krasnoyarskaya HPP - 6000 MW);
- Volga river (Ivankovskaya HPP - 28.8 MW; Uglich HPP - 120 MW; Rybinsk HPP - 356.4 MW; Nizhny Novgorod HPP - 520 MW; Cheboksary HPP - 1374 MW; Zhigulevskaya HPP - 2456.5 MW; Saratovskaya HPP - 1403.78 MW; Volzhskaya HPP - 2660.5 MW);
- Kama river (Kamskaya HPP - 552 MW; Votkinsk HPP - 1035 MW; Nizhnekamskaya HPP - 1205 MW).
It is worth noting that the above-described 4 cascades of hydropower plants play a key role in the reliable and uninterrupted functioning of the energy system of Russia. The Volga-Kama cascade of hydropower plants is one of the largest cascades of hydropower plants in the world. The cascade is located on the Volga River and its tributary Kama River. In this case, the cascade of hydropower plants is located in the territories of 18 central regions of Russia. Electricity generation by hydroelectric power stations of the cascade exceeds 37 billion kWh per year. The cascade consists of 8 large hydropower plants on the Volga River: Ivankovskaya HPP, Uglich HPP, Rybinsk HPP, Nizhny Novgorod HPP, Cheboksary HPP, Zhigulevskaya HPP, Saratovskaya HPP and Volzhskaya HPP and 3 hydropower stations on the Kama River – Kamskaya HPP, Votkinskaya HPP and Nizhnekamskaya HPP (Figure 1).

![Figure 1. Location of the Volga-Kama cascade of hydropower plants on the Volga River and the Kama River in the central European part of Russia.](image)

The Volga River, with its length from the source to the mouth of 3,531 km, is the first in length in Europe. It originates on the Valdai Hills near the village of Volgoverkhovye (228 m above sea level) and flows into the Caspian Sea at 28 m below sea level. The total fall of the river is 256 m. The basin of the Volga River is 1,360 thousand km2 (136 million hectares), which exceeds the territory of France, Spain and Italy combined, and unites 151,000 rivers, streams and drains, more than 90% of them falls on rivers less than 10 kilometers long. The total length of the river with its tributaries is 574,000 km.

63 million people live on the borders of the Volga-Kama cascade. More than 60% of the industrial potential and half of Russia's agricultural potential are concentrated in the nearby territories of the cascade.

At the HPP of the cascade there is a high degree of regulation of the river flow. This circumstance is due to the presence of large reservoirs, which are operated within the framework of daily, weekly and seasonal regulation.

2. The role of the Volga-Kama cascade of hydropower plants in the work of the unified energy system of Russia
The HPPs of the cascade play a key role in the work of the Unified Energy System of Russia. As a result of the construction of hydropower plants, the local energy systems of the European part were merged into the Unified Energy System (UES). Power supply of local (regional) consumers at hydroelectric power stations is carried out at a voltage of 220 kV. The 500 kV power lines unite the country's local energy systems.
3. The role of the Volga-Kama cascade of hydropower plants in the work of water management systems

The operation of hydropower plants of the Volga-Kama cascade is not limited to the interests of exclusively energy systems, it has a multifactorial use. In the framework of the HPP cascade, the interests of the following systems should be ensured: ecology, agriculture, municipal and industrial water supply, river transport (freight and passenger), fisheries, etc.

The interests of the fisheries are to maintain the reservoirs of cascade hydroelectric power stations during the spawning period of the fish at the same level without significant fluctuations within the periods. At the same time, in winter, in order to prevent fish from freezing, the fish industry is interested in a late (closer to the spring flood) decrease in the water level of the reservoirs.

The interests of agriculture are limited to withdrawing water from reservoirs for the purpose of irrigating fertile land. The water level at the upper and lower pools of the waterworks should ensure continuous operation of pump irrigation systems.

River transport (freight and passenger) has restrictions on the water levels at the upper and lower pools of the waterworks, as well as on the water flow rate through the hydropower stations, to conduct safe locking of ships. An additional limitation is the mark of the navigation level, below which the water level of the reservoir cannot fall during navigation. At the same time during the spring flood the reservoir should be filled as soon as possible.

Restrictions on municipal and industrial water supply are imposed in terms of ensuring the water level in the reservoir is above the minimum level of water intakes. In addition, at each HPP, depending on its characteristics and flow hydrology, the average daily minimum water flow rate are determined (8-12).

It should be noted that the above requirements of water management systems can be imposed not only on the cascade of hydropower plants, but also individually for each hydroelectric station.

Thus, the operation of a cascade of hydropower plants serving energy, environmental and water management systems has a complex form of satisfying the interests of all parties.
In accordance with the water law of the Russian Federation, the “Basic rules for the use of water resources” (hereinafter BRUWR) reservoirs should be developed for each HPP. This document regulates the order of distribution of water resources of the reservoir among its consumers (both energy and water management). In this case, BRUWR describes the operation of an individual reservoir, not taking into account the cascade connection of hydroelectric power plants.

At present, there is no practice of drawing up rules for operating a complex of a hydroelectric station cascade. The presence of individual BRUWR for each reservoir does not allow solving the tasks of complex optimal distribution of water resources among consumers of energy and water management complexes taking into account the interests of ecology. From year to year this circumstance increasingly aggravates the contradictions between the participants of water management activities, which in turn leads to a deterioration in the operating mode of the hydropower complex of the UES of Russia, and to a deterioration of the ecological and economic situation of the water management complex (13).

4. Analysis of the key problems of the formation of optimal modes of operation of the hydropower plants cascade

At present, there is no effective model for the operation of the hydropower complex of the hydroelectric power station cascade, which makes it possible to equally take into account the interests of all water users. The existing methods for optimizing the operating modes of a hydroelectric power station cascade either have lost their relevance or satisfy the interests of a specific circle of water users. The optimization model should take into account the interests of all water users of water resources. At the same time, it is obvious that, depending on various conditions (time of year, water inflow, etc.), the number of water users' requirements may vary both upwards and downwards. Thus, we obtain an optimization problem, with an indefinite number of optimality criteria.

5. The method of successive concessions and the algorithm for calculating the modes of operation of the hydropower plant cascade

A specific feature of the problem under consideration is the presence of a multiplicity of external conditions that require consideration of many requirements (criteria). At the same time, depending on the external and internal conditions, the number of requirements may be different.

The optimality criteria $R_{ij}$ and the objective functions for individual participants of water consumption, besides hydropower plants, are quantitatively very difficult to express. However, it is obvious that they are functions of water flow $Q_{ij}$ in each HPP and in each time period, i.e. $R_{ij} = R_{ij}(Q_{ij})$. Participants of water consumption can specify requirements for water flow rate $Q_{ij}$ or levels $Z_{ij}$ or power generation $P_{ij}$, providing for them an effect maximum. Requirements can be expressed both in the form of maximization / minimization of the parameter, and in the form of restrictions.

In this case, the problem of optimal distribution of water runoff between HPP is reduced to a compromise satisfaction of the requirements for $Q_{ij}$ or $Z_{ij}$ or $P_{ij}$ for all participants of water consumption. The resulting water distribution can be considered a compromise solution to the multi-criteria optimization problem. To solve the problem, a technique has been developed for successive concessions in distributing the water flow between all HPP of the cascade in each time period. The algorithm for forming the operating modes of the hydroelectric power station cascade is reduced to the phased implementation of a number of the tasks described below.

1. At the first stage, the calculation period is set. This calculation period is divided into $n$ discrete intervals. It is obvious that the longer the duration of the calculated intervals (therefore, the smaller the number of intervals), the smaller the complexity of the solution, but the greater the error. It is best to determine the duration of the intervals by experimental calculations. In the general case, the duration of the calculated intervals may be longer under conditions of minimal variability in river flow time and maximum regulatory capacity of the reservoirs.
2. At the next stage, the indices i and j determine the number of the calculated interval and the number of hydroelectric power plants (all the hydroelectric power stations of the cascade are numbered from top to bottom, or by elevation levels in the Baltic system). Thus, i settlement intervals and j hydropower stations are considered.

3. Next, the values of the hydrographs of the rivers, as well as the requirements of the water users to establish the operating modes of the individual hydroelectric complexes of the cascade for the forthcoming period, are entered into the model. These requirements are formed in the form of a mathematical description of the conditions of optimality or limitations of the system.

4. In the next step, the source data is imported (loaded) into the model. Data loading is carried out on all HPPs of the cascade prior to the beginning of the calculation period. Thus, at the beginning of the calculation period, all the parameters necessary for the calculation should be determined. In case of delay in the flow of water between the stages of the HPP cascade, it is also necessary to set the flow rate of water to the lower pools of the HPP for several preceding calculation intervals. End conditions can also be specified in the form of reservoir levels at the end of the billing period.

After the data is loaded, the parameters are processed, followed by updating the existing characteristics. The update algorithm is incorporated in the developed software product, the calculation process takes a short time. A check is carried out on the adequacy of the model and the achievement of prediction of the main parameters within the limits of acceptable intervals.

5. Further, experts carry out a qualitative analysis of the relative importance (priority) of the requirements of each water user of the cascade. Based on this analysis, the requirements of the participants are numbered in decreasing order of importance (priority) R1, R2, R3 ... ..Rn (Table 1).

| Priority number | Water user requirement                                      |
|-----------------|------------------------------------------------------------|
| 1               | R1(Q1,j...Qi,j) = Wj → max/min;                           |
| 2               | R2(Q1,j...Qi,j) = Wj → max/min;                           |
| 3               | R2(Q1,j...Qi,j) = Wj → max/min;                           |
| ...             | ...                                                        |
| n               | Rn(Q1,j...Qi,j) = Wj → max/min;                           |

6. Next, the task of finding a solution to the first ranking requirement R1(Q1,j...Qi,j) = Wj → max/min is solved, where (W – is the water consumption Qj or the level Zj). The calculation is carried out for the entire cascade of waterworks throughout the settlement period.

7. At the next stage, the value of the “permissible” concession ΔW1 of the requirement R1(Q1,j...Qi,j) is assigned. Further, the problem of finding the solution of the second most important requirement R2(Q1,j...Qi,j) = Wj → max/min is solved, provided that the parameter of the first requirement should be no more / less (depending on the condition of maximizing or minimizing the requirement), than R1 +/- ΔW1 and this condition is a restriction:

\[
R_2(Q_{i,j}...Q_{i,j}) = W_j \rightarrow \text{max} / \text{min};
\]

\[
R_1(Q_{i,j}...Q_{i,j}) \geq R_1 - \Delta W_1 \text{ or } R_1(Q_{i,j}...Q_{i,j}) \leq R_1 + \Delta W_1;
\]

\[
\Delta W_1 \geq 0.
\]

8. At the next stage, the value of the “permissible” concession ΔW2 of the requirement R2(Q1,j...Qi,j) is assigned. Further, the problem of finding the solution of the third requirement R3(Q1,j...Qi,j) = Wj → max/min is solved, provided that the second requirement parameter must be no more / less (depending
on the condition of maximizing or minimizing the requirement) than $R_2 +/- \Delta W_2$ and this condition is a restriction:

$$R_j(Q_{i,j}...Q_{i,j}) = W_j \rightarrow \max / \min;$$

$$R_1(Q_{i,j}...Q_{i,j}) \geq R_1 - \Delta W_1 \text{ or } R_1(Q_{i,j}...Q_{i,j}) \leq R_1 + \Delta W_1;$$

$$R_2(Q_{i,j}...Q_{i,j}) \geq R_2 - \Delta W_2 \text{ or } R_2(Q_{i,j}...Q_{i,j}) \leq R_2 + \Delta W_2;$$

$$\Delta W'_i \geq 0 \Delta W_2 \geq 0.$$ 

And so on, until the task of the last requirement of water users of the cascade is solved:

$$R_k(Q_{i,j}...Q_{i,j}) = W_j \rightarrow \max / \min;$$

$$R_1(Q_{i,j}...Q_{i,j}) \geq R_1 - \Delta W_1 \text{ or } R_1(Q_{i,j}...Q_{i,j}) \leq R_1 + \Delta W_1;$$

$$R_2(Q_{i,j}...Q_{i,j}) \geq R_2 - \Delta W_2 \text{ or } R_2(Q_{i,j}...Q_{i,j}) \leq R_2 + \Delta W_2;$$

$$......$$

$$R_k(Q_{i,j}...Q_{i,j}) \geq R_k - \Delta W_k \text{ or } R_k(Q_{i,j}...Q_{i,j}) \leq R_k + \Delta W_k \ k = 1, n-1$$

$$\Delta W'_i \geq 0 \Delta W_2 \geq 0 \ldots \Delta W'_k \geq 0 \ k = 1, n-1$$

At the same time, for each pair of sequentially analyzed requirements, it is necessary to specify several values of the concessions $\Delta W_k$ and determine the changes in the maximum values of $\Delta W_{k+1}$ taking into account the significance of the requirements considered.

It is obvious that there is a probability of a situation in which the solution of the problem will be completed before reaching the last requirement. Under these conditions, an increase in the value of the assignment leads either to the achievement of the limit value, or in principle does not lead to the solution of the problem. In this case, the problem is solved for the $k$th number of criteria within the framework of previously approved assignments.

The mathematical apparatus of the method allows to solve the sequence of the above described problems of mathematical programming. Consequently, its use allows you to generate different solutions for various combinations of conditions, and the analysis of the quantitative characteristics of these options makes it possible to select the most representative ones.

In this case, the problem of optimal distribution of runoff between waterworks is reduced to a compromise satisfaction of the requirements for $Q_{ij}$ and $Z_{ij}$ for all water users of the cascade. The resulting distribution of water and levels can be considered a compromise solution to the multi-objective optimization problem.

Thus, the task of optimally distributing the runoff between the waterworks of the cascade in a deterministic formulation is reduced to determining the mode of operation of the HPP cascade in which the maximum possible number of requirements ranked by importance are implemented. In addition, the specified mode constraints are satisfied.

It should be noted that the task of finding a solution for the $k$-th requirement of the participant, taking into account all the limitations and assumptions, is solved using simulation modeling.

The simulation approach to solving the problem consists of the following steps:

- the values of the parameter $Q_{ij}$ are set for all waterworks of each calculation period;
- within the framework of the specified requirements of the water user of the cascade and the existing restrictions, water-energy calculation is performed;
• the values of the parameter \( Q_{ij} \) change. A new calculation is being performed;
• from the obtained set of indicators of water and energy regimes of the hydroelectric station cascade choose a set of indicators that most closely meet the specified requirement of the water user when all restrictions and assumptions are fulfilled.

The main advantages of simulation modeling include the possibility of its use in cases where the nature of the processes occurring in the system does not allow to describe these processes in an analytical form. Moreover, simulation modeling makes it possible to more actively involve in the process of developing management rules the specialists who form the modes of operation of the HPP cascade. This circumstance allows using their intuition, experience and knowledge for practical application of the obtained calculation results.

6. **Economic efficiency for hydropower**

It should be noted that the software product is operated in JSC "Tatenergo" (Russia) to calculate the operating modes of the Nizhnekamsk hydroelectric station. Software solution has shown its economic efficiency. The economic effect from the author’s implementation of the rationalization proposal “study of optimal power limitations of cascade hydropower plants taking into account the current vibration state of generating equipment under the current wholesale market regulations” amounted to 99.9 million rubles (~ $1.515 million) in the first year of implementation, and in the second year implementation of 99.1 million rubles (~ 1.503 million dollars). The economic effect from the author’s implementation of the rationalization proposal “the automated system for planning the daily load of hydroelectric power plants in the context of differentiated prices for electricity” in the first year of implementation amounted to 3.4 million rubles (~ 51.5 thousand dollars), in the second year of implementation 3.3 million rubles (~ 50 thousand dollars). Thus, the average annual economic effect from the implementation of the rationalization proposals by the author, operating on the basis of the methods developed in this work, is ~ 102.85 million rubles (~ 1.559 million dollars) annually.

7. **Program complex for calculating the modes of operation of a hydroelectric station**

The software product developed within the framework of the above task is characterized by the presence of mathematical, software, informational, and technical software.
The software package is implemented in ASP.NET C# language using MVC technology. Database: MSSQL Server, web server: IIS (Internet Information Server). Access to the software package is provided from any web browser at http://hydrocascade.com.

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