Optimization of operating modes of hydropower plants with determination of the price for a hydro resource using complex criteria of ecological and economic efficiency

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Abstract. At present, the influence of technologies on the environment became comparable with natural processes at the Earth. Therefore, the use of renewable energy sources, including water resources, is very important for the energy market operated as the Internet of things. The present paper proposes a universal method for analyzing the efficiency of technical systems using the combination of an optimization method and a method of marginal utility evaluation. Based on the comparison of water volume at a hydropower plant (HPP) and fuel amount at a combined heat and power plant (CHPP) that is used for generation of 1 kW power, it is possible to determine a water price for a HPP. Using the examples of Novosibirsk HPP and CHPP, it is expected to develop an estimation of economic effect from the implementation of the developed criteria, the proposed method of determination of a water price at HPP, and the method of separating fuel costs at CHPP. As a result of implementing the developed method for the HPP, the price of sold electricity in the flexible energy market will be comparable with the price for sold electricity produced at the CHPP, being equal to approximately 330 RUB/MW∙h. Moreover, CHPP are expected to have savings of specific fuel consumption for electricity generation in the amount of 5 g/kW∙h and, in some case, 10 g/kW∙h. In terms of money, this amounts about 7,350,000 – 14,700,000 RUB per month.

1. Introduction

This paper provides the review and development of the method for estimating the price of water at a HPP during optimization of operating conditions based on complex criteria of ecological-and-economic efficiency under modern conditions. At present, the influence of technologies on the environment became comparable with natural processes at the Earth. Therefore, the use of renewable energy sources, including water resources, is very important for the energy market operated as the Internet of things [1, 2]. One of the universal methods of analyzing the efficiency of technical systems is the optimization method in combination with the theory of marginal utility. This allows determining a water price for a HPP based on the comparison of water consumed at a HPP and fuel amount required at a CHPP for generation of 1 kW power. It is possible only to reduce exergy of these flows to the reasonable limit determined by damping properties and elasticity of nature for their transformation into intermediate and conditionally end products, which are human- and environment-friendly, in other words, by electricity co-generation at a HPP and a CHPP [3, 4].
2. The Model of Functioning Management for Power Plants

This investigation proposes an ecological-and-economic profit maximization criterion for optimal load dispatching (or management) of hydropower and thermal power plants under modern conditions, and a strategy for controlling a water price at a HPP using the theory of marginal utility [5, 6].

According to the profit maximization criterion, a producer will maximize its profit when producing goods at the point where marginal revenue equals marginal costs [7-9]. This leading principle of profit maximization is called as the rule of equality between marginal revenue and marginal costs. This principle is illustrated in Figure 1.

Marginal revenue (MR) is determined by a differential curve of energy demand, while marginal costs are influenced by a derivative component of energy production costs. The latter may be represented by an incremental fuel costs characteristic for thermal power plants [10, 11]. All these values have the same dimension (price/prod.unit), thus they may be comparable for calculations [12].

![Figure 1. Determination of the optimal production output](image)

The optimal energy production output \( E_{\text{opt}} \) allows an energy enterprise to maximize its profit. Assume that less goods \( E_1 \) are produced in comparison with an optimal output at higher price \( P_1 \). In this case, marginal revenue of the producer exceeds marginal costs. If production output raises up to \( E_{\text{opt}} \) (when profit from selling one additional product unit equals to zero), the producer will increase the total profit by the square abc.

Production output \( E_2 \) being greater than the optimal level does not also maximizes profit, because marginal costs exceeds marginal revenue. Increase of profit due to reduction of production output down to \( E_{\text{opt}} \) instead of \( E_2 \) corresponds to the value, which is equal to the square bde.

Under modern conditions, each business unit is interested in the increase of its own profit, therefore the proposed method allows determining production outputs at a power plant with a glance to modern features of Russian power engineering [13].

Exergy allows combining the three aspects of optimization: thermodynamic, technical-and-economic and ecological – within the unified optimization system [14, 15]. Water resources are very important for saving primary energy resources and material resources at the input of the technical system. In the end, they reduce the harmful impact on humans and the environment. The general rule can be stated as follows: it is more profitable to save primary energy and material resources during implementation of technological processes as close to end sections as possible. In other words, 1 kW∙h of electricity (in RUB) is more expensive at the end of the technological chain, than at the beginning.

During the scientific research, the following general problems were solved: 1. The criterion instruments for complex estimation and optimization of electricity and heat generation at a CHPP and ele-
tricity at a HPP were proved on the basis of the exergy approach with justification of the conceptual system for “environmental parameters”. 2. The method for calculation of a water price for a HPP was developed that allows not only improving ecological situation in the region, but also increasing competitiveness of power plants. 3. The urgency of the concept of “marginal utility” used for calculation of a water price for HPP was substantiated. 4. The mathematical instruments were developed for exergy optimization of the complex efficiency for processing primary resources on the basis of interconnected thermodynamic and ecological-and-economic criteria in order to generate electricity and heat, and a fundamentally new method of separating fuel costs between the considered types of energy at CHPP was presented. 5. The developed exergy-and-economic and technical criteria were tested to compare various technologies for generating electricity and heat based on the optimization of operating conditions of CHPP and HPP. 6. The model was developed for launching HPP and CHPP to the competitive electricity market on the basis of solving two important and interrelated problems for managing power plant operating conditions.

The formulated problems and stages of their implementation are presented in Figure 2.

Based on the developed methodology, the power plant can solve two important and interrelated problems during the optimization of operating conditions: 1) Determine the optimal range of electricity generation at power plants at an electricity tariff, which is formed in the flexible market; 2) Based on the optimal electricity generation at power plants, it is possible to substantiate the value of a posted price in the competitive market.

3. The model for evaluating the price of a hydro resource for HPP operation in the power system

At present, a problem of optimal load distribution between HPP and CHPP in the power system is solved in the following way:

\[
\begin{align*}
\mathbf{b} &= \lambda \mathbf{q}, \\
\mathbf{Q}_{\text{HPP}} &= \mathbf{Q}_{\text{GIV}}, \\
\mathbf{P}_{\text{S}} &= \mathbf{N}_{\text{CHPP}} + \mathbf{N}_{\text{HPP}}, \\
\mathbf{N}_{\text{CHPP}}_{\text{min}} &\leq \mathbf{N}_{\text{CHPP}} \leq \mathbf{N}_{\text{CHPP}}_{\text{max}}, \\
\mathbf{N}_{\text{HPP}}_{\text{min}} &\leq \mathbf{N}_{\text{HPP}} \leq \mathbf{N}_{\text{HPP}}_{\text{max}}, \\
\lambda &= \text{const}
\end{align*}
\]

where:

\( \mathbf{b} \) and \( \mathbf{q} \) – incremental rate characteristics for water and fuel at a CHPP and a HPP respectively; 
\( \mathbf{P}_{\text{S}}, \mathbf{N}_{\text{CHPP}}, \mathbf{N}_{\text{HPP}} \) – power system load, values of power served by a CHPP and a HPP respectively; 
\( \mathbf{N}_{\text{CHPP}}_{\text{min}}, \mathbf{N}_{\text{CHPP}}_{\text{max}}, \mathbf{N}_{\text{HPP}}_{\text{min}}, \mathbf{N}_{\text{HPP}}_{\text{max}} \) – minimum and maximum power for a CHPP and a HPP respectively; 
\( \mathbf{Q}_{\text{GIV}} \) – permissible water flow rate at a HPP determined by water-power calculations; 
\( \mathbf{Q}_{\text{HPP}} \) – water flow rate at a HPP; 
\( \lambda \) – the Lagrangian multiplier.

In this case, \( \mathbf{b} \) and \( \mathbf{q} \) have different dimensions. Therefore, it is necessary to experimentally select the value of \( \lambda \) taking into account the limited hydro resources at the HPP. These circumstances lead to a serious complication of calculations associated primarily with an increase in the number of iterative procedures and the convergence of this process.

The paper proposes the other method for solving this problem.

In relation to our research, we will consider water and fuel as products used for generation of the same amount of electricity.

The above-mentioned considerations regarding marginal utility can be presented in a very simple graphical form (see Figure 3).
Moreover, it should be noted that it is necessary to convert physical quantities $1/q$ [s*kW/m$^3$] and $1/b$ [kW*h/ton of coal equivalent] into relative units, since this will allow comparing the indifference curve represented in relative units and the incremental rate characteristics for water at the HPP ($q$) and fuel at the CHPP ($b$) in one diagram (see Figure 4). When plotting the incremental rate characteristics for water at the HPP and fuel at the CHPP, the current values of incremental rates were divided by the average incremental rates of water and fuel, respectively.

Combining three curves in one diagram (i.e. the indifference curve and the incremental rate characteristics for water at the HPP and fuel at the CHPP), we obtain a new rule for the transition from the incremental water rate to the incremental fuel rate without using the Lagrangian multiplier $\lambda$. The value of the incremental water rate at the HPP $q'$ locating on the indifference curve (see Figure 4) will be equal to the corresponding value of the incremental fuel rate at the CHPP locating on the same curve, since water and fuel in this case will have the same importance to the consumer.
Moreover, in order to obtain the corresponding power value for a particular hour according to the
daily load schedule, it is necessary to shift the indifference curve in parallel to itself.

Figure 4. Incremental rate characteristics for water at the HPP and fuel at the
CHPP combined with the indifference curve.

Then, using the indifference curve for marginal costs of water and fuel consumption, it should be
noted that the slope of the indifference curve remains exactly the same.

Hence, the water price for a HPP can be determined using the following curve (see Fi-
gerure 5) and
expression (2).

\[ U_q = w_p q \]  

(2)

where:
\( U_q \) – marginal costs at a HPP;
\( q \) – incremental water rate at a HPP;
\( w_p \) – water price for a HPP.

Figure 5. Indifference curve (for marginal cost): where \( U_q \) – marginal costs at a HPP, \( U_b \) – marginal costs at a CHPP, \( b \) – incremental fuel rate at a CHPP, \( q \) – incremental water rate at a HPP, \( w_p \) – water price for a HPP.

Figure 6 shows the indifference curve and the incremental rate characteristics for water at the HPP
and fuel at the CHPP in relative units using the example of the high-water period.

The indifference curve in relative units for the high-water period is illustrated in Figure 7.

Since for any HPP the daily consumption of water resource is uniquely determined, the problem of
choosing the optimal HPP operating conditions is solved in the same way as for a CHPP with a given
fuel consumption. According to the developed methodology, it is necessary to plot the incremental water
rate characteristics for a given structure of operating equipment at the HPP for each optimization inte-
val, which is a month or a decade for the period of filling the HPP reservoir. To verify the operability of
the proposed model, the simplified HPP operating modes were used, in particular, seasonal periods of the
year (Figure 8).

Taking into account the price of water obtained using the proposed model, it is necessary to plot the
marginal costs characteristics for water flow rate at the HPP, and then obtain the optimal amount of
electricity generation at the HPP (Figure 9).
Figure 6. The indifference curve and the incremental rate characteristics for water at the HPP and fuel at the CHPP in the high-water period.

Figure 7. The indifference curve for the high-water period.

Figure 8. Incremental water rate characteristic for the Novosibirsk HPP for the high-water period.
Based on the developed complex criteria of ecological-and-economic efficiency, the optimal amount of electricity generation at the HPP was obtained using the high-water period as an example (Figure 10). Electricity generation at the Novosibirsk HPP in the high-water period varies from 100800 to 114480 MW·h. An electricity price for that period equals from 257 to 270 RUB/MW·h. As for the low-water period, electricity output is from 90000 to 100800MW·h with the posted price varied from 600 to 689 RUB/MW·h. Being operated with natural river flow, these values are equal to 93000 – 97200 MW·h and 290 – 300 RUB/MW·h.

The results of calculations are given in Table 1.

Table 1. Optimal Values of Power Output for the Novosibirsk HPP by Year seasons.

| Season               | High-water period | Low-water period | Operation with natural river flow |
|----------------------|-------------------|------------------|-----------------------------------|
| Profit rate          | 0%                | 12%              | 0%                                |
| Power, MW            | 140               | 159              | 125                               |
| Electric energy, MW·h| 100 800           | 114 480          | 90 000                            |
| Posted price, RUB/MW·h| 257              | 270              | 600                               |
| Revenue, RUB         | 77 716 800        | 92 728 800       | 378 000 000                      |
| Profit, RUB          | 15 012 000        | 108 158 400      | 4 032 000                        |

An analysis of the results obtained by optimizing the operating conditions of the Novosibirsk CHPP showed that it is reasonable for the Novosibirsk CHPP No.2 to produce 216 MW (348942 Gcal) in winter, 91 MW (79149 Gcal) in summer, and 146 MW (191910 Gcal) in the transition season; the optimal load for the Novosibirsk CHPP No.4 is 253 MW (356589 Gcal) in winter, 59 MW (82282 Gcal) in summer, and 210 MW (264725 Gcal) in the transition season [5, 6]. It is these operating conditions that will allow the power plants to get the maximum profit for each season of the year.
To verify the developed methodology, it is necessary to compare the found values of the average daily water flow rate, which are obtained after the distribution of the daily load of the generation company between the HPP and the equivalent CHPP according to the developed methodology, with the specified guaranteed value of the water flow rate at the HPP.

The results of the implementation of the developed methodology are given below for the example of the Siberian Generation Company (SGC), where the Novosibirsk CHPP No.2, No.3, No.4, and No.5 were taken as the equivalent CHPP and the Novosibirsk HPP was operated in the high-water period, low-water period, and with natural river flow (Figures 11-13).

**Figure 10.** Curves for determination of optimal amounts of electricity generation for the high-water period at the Novosibirsk HPP.

**Figure 11.** Schedule of daily power distribution of the SGC between the Novosibirsk HPP and the equivalent CHPP for the high-water period.
Figure 12. Schedule of daily power distribution of the SGC between the Novosibirsk HPP and the equivalent CHPP for the low-water period.

In table 2 the daily power distribution of the SGC between the Novosibirsk HPP and the equivalent CHPP for the high-water period is given.

The calculation results showed that the comparison of the average daily water flow rate obtained by the developed methodology with the specified guaranteed water flow rate for each period gave an error of about 8% for the high-water period, 4% for the low-water period, and 10% for operation with natural river flow, being amounted to 2793,9 m³/s for the high-water period, 323 m³/s for the low-water period, and 1456,147 m³/s for operation with natural river flow. This indicates the reliability of the results according to the developed methodology and allows making a conclusion about its validity and the possibility for application of the methodology to determination of the price for water as a hydro resource taking into account the operational features of HPP based on complex criteria of ecological and economic efficiency.

The results of the implementation of the Lagrangian multiplier method are given below for the example of the Siberian Generation Company (SGC), where the Novosibirsk CHPP No.2, No.3, No.4, and No.5 were taken as the equivalent CHPP and the Novosibirsk HPP was operated in the high-water period, low-water period, and with natural river flow (see Figures 14-16).
Table 2. Power Distribution in the SGC between the Novosibirsk HPP and the Equivalent CHPP for the High-Water Period.

| T, hour | Q, m³/s | $N_{SGC}$, MW | $N_{HPP}$, MW | $N_{CHPP}$, MW | Base spill power of HPP = 5%, MW |
|---------|---------|---------------|---------------|----------------|----------------------------------|
| 1       | 1992.77 | 1142.08       | 250.00        | 892.08         | 12.50                            |
| 2       | 1992.77 | 1108.94       | 250.00        | 808.00         | 12.50                            |
| 3       | 1992.77 | 1097.30       | 250.00        | 859.20         | 12.50                            |
| 4       | 1992.77 | 1142.08       | 250.00        | 859.20         | 12.50                            |
| 5       | 1992.77 | 1333.41       | 250.00        | 1093.70        | 12.50                            |
| 6       | 1992.77 | 1475.13       | 250.00        | 1225.13        | 12.50                            |
| 7       | 2853.49 | 1655.30       | 358.00        | 1297.30        | 17.90                            |
| 8       | 2853.49 | 1657.00       | 358.00        | 1299.00        | 17.90                            |
| 9       | 2853.49 | 1658.50       | 358.00        | 1378.82        | 17.90                            |
| 10      | 2853.49 | 1658.00       | 358.00        | 1378.00        | 17.90                            |
| 11      | 2853.49 | 1647.79       | 358.00        | 1369.79        | 17.90                            |
| 12      | 2853.49 | 1648.91       | 358.00        | 1290.91        | 17.90                            |
| 13      | 2853.49 | 1648.00       | 358.00        | 1290.00        | 17.90                            |
| 14      | 2152.16 | 1589.91       | 270.00        | 1312.11        | 13.50                            |
| 15      | 2152.16 | 1548.08       | 270.00        | 1278.08        | 13.50                            |
| 16      | 2152.16 | 1553.21       | 270.00        | 1283.21        | 13.50                            |
| 17      | 2152.16 | 1561.22       | 270.00        | 1291.22        | 13.50                            |
| 18      | 2152.16 | 1562.98       | 270.00        | 1292.98        | 13.50                            |
| 19      | 2152.16 | 1593.38       | 270.00        | 1323.38        | 13.50                            |
| 20      | 2853.49 | 1636.90       | 358.00        | 1278.90        | 17.90                            |
| 21      | 2152.16 | 1543.57       | 270.00        | 1304.44        | 13.50                            |
| 22      | 2072.46 | 1414.87       | 260.00        | 1154.87        | 13.00                            |
| 23      | 1992.77 | 1298.05       | 250.00        | 1048.05        | 12.50                            |
| 24      | 1992.77 | 1230.14       | 250.00        | 980.14         | 12.50                            |

Figure 14. Schedule of daily power distribution of the SGC between the Novosibirsk HPP and the equivalent CHPP for the high-water period according to the Lagrangian multiplier method.
In table 3 the daily power distribution of the SGC between the Novosibirsk HPP and the equivalent CHPP for the high-water period according to the Lagrangian multiplier method is given.

Similar calculations using the conventional methodology for distributing the load of the power system between its power plants by the Lagrangian multiplier method showed comparable results. For this methodology, there is an increase in the share of CHPP in electricity production for the needs of an electricity consumer and an increase of the error when comparing the average daily water flow rate obtained by the Lagrangian multiplier method with the specified guaranteed value of water flow rate for each period. The comparison gave an error of about 10% for the high-water period, 7% for the low-water period, and 10% for operation with natural river flow, being amounted to 2329.48 m$^3$/s for the high-water period, 333.195 m$^3$/s for the low-water period, and 1182.58 m$^3$/s for operation with natural river flow.

It is necessary to note that the quantity of Novosibirsk HPP in covering the daily power schedule according to the developed methodology increases in 20% (20% for the high-water period, 22% for the low-water period, and 18% for operation with natural river flow) comparison with the traditional Lagrangian methodology.
Table 3. Power Distribution in the SGC between the Novosibirsk HPP and the Equivalent CHPP for the High-Water Period according to the Lagrangian Multiplier Method.

| T, hour | Q, m³/s | N_{SGC}, MW | N_{HPP}, MW | N_{CHPP}, MW | Base spill power of HPP = 5%, MW |
|---------|---------|-------------|-------------|-------------|----------------------------------|
| 1       | 1281.89 | 1194.46     | 186.67      | 1007.79     | 9.33                             |
| 2       | 1362.28 | 1298.44     | 196.00      | 1102.44     | 9.80                             |
| 3       | 1450.39 | 1394.86     | 206.00      | 1188.86     | 10.30                            |
| 4       | 1513.27 | 1450.36     | 213.00      | 1237.36     | 10.65                            |
| 5       | 1522.33 | 1457.01     | 214.00      | 1243.01     | 10.70                            |
| 6       | 1517.80 | 1456.50     | 213.50      | 1243.00     | 10.68                            |
| 7       | 1495.20 | 1438.08     | 211.00      | 1227.08     | 10.55                            |
| 8       | 1698.38 | 1485.82     | 233.00      | 1252.82     | 11.65                            |
| 9       | 1486.20 | 1437.60     | 210.00      | 1227.60     | 10.50                            |
| 10      | 1490.70 | 1425.74     | 210.50      | 1215.24     | 10.53                            |
| 11      | 1604.81 | 1472.21     | 223.00      | 1249.21     | 11.15                            |
| 12      | 1698.38 | 1487.08     | 233.00      | 1254.08     | 11.65                            |
| 13      | 1793.97 | 1519.81     | 243.00      | 1276.81     | 12.15                            |
| 14      | 1929.29 | 1621.81     | 256.81      | 1365.00     | 12.84                            |
| 15      | 1862.08 | 1573.58     | 250.00      | 1323.58     | 12.50                            |
| 16      | 1459.31 | 1404.59     | 207.00      | 1197.59     | 10.35                            |
| 17      | 1310.38 | 1266.40     | 190.00      | 1076.40     | 9.50                             |
| 18      | 1233.90 | 1137.73     | 181.00      | 956.73      | 9.05                             |
| 19      | 1192.11 | 1121.32     | 176.00      | 945.32      | 8.80                             |
| 20      | 1159.05 | 1076.79     | 172.00      | 904.79      | 8.60                             |
| 21      | 1167.28 | 1088.93     | 173.00      | 915.93      | 8.65                             |
| 22      | 1165.64 | 1087.23     | 172.80      | 914.43      | 8.64                             |
| 23      | 1207.93 | 1146.04     | 177.90      | 968.14      | 8.90                             |
| 24      | 1344.90 | 1278.25     | 194.00      | 1084.25     | 9.70                             |

Therefore, it can be concluded that the developed methodology allows not only determining a price of a hydro resource using the operational features of the HPP, but also solving energy-saving and ecological problems.

4. Results

The present paper proposes a universal method for analyzing the efficiency of technical systems using the combination of an optimization method and a method of marginal utility evaluation. Based on the comparison of water volume at a hydropower plant (HPP) and fuel amount at a combined heat and power plant (CHPP) that is used for generation of 1 kW power, it is possible to determine a water price for a HPP.

Practical testing of the developed method at the Novosibirsk HPP results in obtaining the following water prices for the HPP by year seasons (high-water period, low-water period, and operation with natural river flow): the water price for the Novosibirsk HPP in the high-water period is 21.59 RUB/m³, in the low-water period – 30.50 RUB/m³, for operation with natural river flow – 33.66 RUB/m³.

The calculation results showed that the comparison of the average daily water flow rate obtained by the developed methodology with the specified guaranteed water flow rate for each period gave an error of about 8% for the high-water period, 4% for the low-water period, and 10% for operation with natural river flow, being amounted to 2793,9 m³/s for the high-water period, 323 m³/s for the low-water period, and 1456,147 m³/s for operation with natural river flow. This indicates the reliability of the re-
results according to the developed methodology and allows making a conclusion about its validity and the possibility for application of the methodology to determination of the price for water as a hydro resource taking into account the operational features of HPP based on complex criteria of ecological and economic efficiency.

Similar calculations using the conventional methodology for distributing the load of the power system between its power plants by the Lagrangian multiplier method showed comparable results. For this methodology, there is an increase in the share of CHPP in electricity production for the needs of an electricity consumer and an increase of the error when comparing the average daily water flow rate obtained by the Lagrangian multiplier method with the specified guaranteed value of water flow rate for each period. The comparison gave an error of about 10% for the high-water period, 7% for the low-water period, and 10% for operation with natural river flow, being amounted to 2329.48 m$^3$/s for the high-water period, 333.195 m$^3$/s for the low-water period, and 1182.58 m$^3$/s for operation with natural river flow.

It is necessary to note that the quantity of Novosibirsk HPP in covering the daily power schedule according to the developed methodology increases in 20% (20% for the high-water period, 22% for the low-water period, and 18% for operation with natural river flow) comparison with the traditional Lagrangian methodology.

Therefore, it can be concluded that the developed methodology allows not only determining a price of a hydro resource using the operational features of the HPP, but also solving energy-saving and ecological problems.

5. Conclusion
The critical analysis of existing criteria for power plant management was carried out. A new approach for managing operating conditions of a power plant was proposed that considers exergy-and-ecological needs of society and takes into account the technological features of the energy industry. The mathematical model of functioning management for hydropower and thermal power plants for short-term optimization of load schedule coverage under the market conditions was developed. The use of the theory of marginal utility was substantiated for calculation of a hydro resource price using the operational features of the HPP based on the developed model.

Using the proposed model allows evaluating a price of a hydro resources at the HPP and greatly simplifying the use of algorithms for solving short-term optimization problems. Proposed approaches and methods were verified and validated mathematically and experimentally. The general statements of the methodology were realized for the specific power facilities.

6. References
[1] Sekretarev U A and Mitrofanov S V 2016 Decision support system for hydro unit commitment 2nd Int. Conf. On Ind. Eng., Applications and Manufacturing (Chelyabinsk: IEEE) 7911424
[2] Sekretarev Y A and Panova Y V 2016 Investigations of possible using a generalized fuzzy interval for analyzing operating conditions of power equipment at hydropower plants 2nd Int. Conf. On Ind. Eng., Applications and Manufacturing (Chelyabinsk: IEEE) 7911025
[3] Sekretarev Y A and Panova Y V 2018 Development of the intelligent decision support system for situation management of hydro units 14th Int. Sci.-Tech. Conf. on Actual Problems of Electronic Instrument Eng. APEIE (Novosibirsk: IEEE) pp 384-8
[4] Sekretarev U A and Mitrofanov S V 2013 Preventive control taking into account of an operational condition power equipment and flowing path of hydropower plant J. of Siberian Federal University. Engineering And Technologies 6(1) 3-14
[5] Moshkin B N, Myatezh T V, Sekretarev Y A and Averbukh M A 2019 Mathematical model of managing of the generating company on the criterion of the profit maximization IOP Conf. Ser.: Mater. Sci. Eng. 552 012016
[6] Sekretarev Y, Sultonov S and Nazorov M 2016 Optimization of long-term modes of hydropower plants of the energy system of Tajikistan 2nd Int. Conf. on Industrial Eng.,
Applications and Manufacturing (Chelyabinsk: IEEE) 7911428
[7] Ghamgeen I R 2018 Inflows and energy demands of dokan hydropower reservoir operation under stochastic conditions 13th ieee Conf. on Ind. Electr. and Appl. (Wuhan: IEEE) 8397804
[8] Malinina T V, Shulginov R N and Yushkov E S 2013 Operating efficiency evaluation of npp integrated with a pumped storage hydropower plant Atomic Energy 115 64-7
[9] Berlin V V and Murav'ev O A 2015 Governing the turbine-generator unit of a small-scale hydropower plant with a long penstock Power Technology and Engineering 49 240-4
[10] Lukutin B V, Shandarova E B, Matukhin D L, Makarova A F and Fuks I L 2016 Operation modes of a hydro-generator as a part of the inverter micro hydropower plant IOP Conf. Ser.: Mater. Sci. Eng. 124(1) 012070
[11] Zhang L, Wu Q, Ma Z and Wang X 2019 Transient vibration analysis of unit-plant structure for hydropower station in sudden load increasing process Mech. Syst. and Signal Processing 120 486-504
[12] Chang J, Wang X, Li Y, Wang Y and Zhang H 2018 Hydropower plant operation rules optimization response to climate change Energy 160 886-97
[13] Balzannikov M I 2017 Research on flow in water intake of a run-of-river hydropower plant MATEC Web Conf. 117 00013
[14] Abakanov T D, Begalinov A B and Abakanov A T 2016 Seismic stability of tunnels at the kapchagai hydropower plant Soil Mechanics and Foundation Engineering 53 60-5
[15] Sekretarev Y, Sultanov S and Shalnev V 2015 Optimal control mode of the Vakhsh hydropower reservoirs to reduce electricity shortage in Tajikistan Appl. Mech. and Materials 792 446-50